



ASTRONOMY TO-DAY

Astron
M.

ASTRONOMY TO-DAY

BY THE ABBÉ
TH. MOREUX

DIRECTOR OF THE OBSERVATORY OF BOURGES
MEMBER OF THE BRITISH ASTRONOMICAL ASSOCIATION

TRANSLATED BY
C. F. RUSSELL, M.A.

LATE FELLOW OF PEMBROKE COLLEGE, CAMBRIDGE

WITH SIXTY-TWO ILLUSTRATIONS



207292
24.11.26

METHUEN & CO. LTD.
36 ESSEX STREET W.C.
LONDON



This Translation First Published in 1926

PRINTED IN GREAT BRITAIN

CONTENTS

CHAPTER	PAGE
INTRODUCTION	ix
I. WHAT IS THE SUN?	I
II. THE INTERIOR PLANETS, MERCURY AND VENUS	39
III. THE EARTH	55
IV. THE MOON	72
V. THE PROBLEM OF MARS	100
VI. THE MINOR PLANETS, OR ASTEROIDS	116
VII. JUPITER	125
VIII. SATURN	139
IX. URANUS AND NEPTUNE	150
X. THE PROBLEM OF DISTANCES IN ASTRONOMY	162
XI. THE COMETS	171
XII. SHOOTING STARS AND METEORITES	191
XIII. THE STARS	199
XIV. THE EVOLUTION OF STARS, AND STELLAR SYSTEMS	212
XV. STAR CLUSTERS	226
XVI. NEBULAE	237
INDEX	251

LIST OF ILLUSTRATIONS

FIG.		PAGE
I	Chart of a portion of the Milky Way	XVI
2	The Photosphere, showing incandescent clouds on the Sun's surface	3
3	Sun-spot, showing the clouds of the Penumbra	6
4	The Chromosphere and Prominences, during a total eclipse	7
5	Spectro-heliogram of the Sun	8
6	Spectro-heliograms of the Photosphere and the layer above it, showing a Sun-spot at different levels	9
7	Periodic curve for Sun-spots and the Corona	10
8	Polar Corona, intermediate Corona, equatorial Corona	11
9	Curves of the solar activity and the melting of the Martian ice-caps	14
10	Curves of the Sun-spots and the drifting Icebergs	15
11	Curves of the solar activity and certain climatological phenomena	21
12	Relations between Sun-spots, Prominences, and the various solar envelopes	30
13	A Sun-spot	32
14	Curves of Sun-spots and vortices due to velocity-differences	34
15	Orbits of the planets of the solar system	38
16	Mercury	41
17	The last Transit of Mercury	44
18	Venus	53
19	Curve, showing movement of the terrestrial pole	59
20	Indented circular cone generated by the movement of the Earth's axis	63
21	Apparatus employed in measuring base-lines	64
22	Curve, showing abnormal deviations of the magnetic needle	68
23	The Apennines, Mt. Caucasus and the Alps, on the Moon	76
24	Three lunar Circuses, Catharina, Cyrillus, and Theophilus	77
25	Vertical cross section of the crater of Copernicus	79
26	Full Moon, showing the lines radiating from Tycho	83
27	Crystal globe cracked by powerful internal pressure	84

FIG.		PAGE
28	Eye-piece of the Coudé equatorial at Paris Observa- tory	86
29	Spherical bladder covered with plaster, showing cracks formed by dilatation	87
30	The same bladder with a thinner layer of plaster	88
31	The same bladder with a drier and thicker layer of plaster	89
32	Globe of clay, showing cracks formed in drying	90
33	Figure to illustrate the formation of the central peak in a lunar circus	92
34	Mars	104
35	Mars	107
36	The Sea of the Sirens (Mars), in detail and as obscured by mist	110
37	Planisphere of Mars	112
38, 39	The Great Red Spot on Jupiter, in June and August, 1904	129
40	Jupiter	131
41	Measurement of the velocity of light by means of Jupiter's satellites	137
42	Saturn	143
43	Determination of the solar parallax	164
44	Measurement of the Sun's parallax by means of a minor planet	167
45	Figure to show that different conics are almost identical near the focus	173
46	Orbits of the principal periodic comets	177
47	Perturbations in the tail of Morehouse's comet	182
48	A comet's tail	185
49	Orbits of the comet 1866, I, and of the Leonids	193
50	Meteorite observed at Bourges	196
51	The Allegan meteorite	197
52	Stellar parallax	201
53	Distribution of stars in the Milky Way	208
54	Section of the Milky Way	209
55	Representation of the Milky Way, with a plan of our Universe	210
56	Classes of stellar spectra	215
57	Orbits of the two components of Sirius	218
58	Curve of luminosity of a variable star	219
59	The Cluster Omega Centauri	230
60	The Cluster Omega Centauri	231
61	Types of star clusters	233
62	A spiral nebula in Ursa Major	243

AUTHOR'S INTRODUCTION

IN the preface of a recent book, one of our most learned university professors described Astronomy as an almost useless science. To consider only the philosophical aspect of the question, the assertion seems to be paradoxical ; for it amounts to a condemnation of the loftiest speculations of human thought, and in its view even the arts could find no favour. To anyone who inquires about the use of music or painting, the artist will reply by a shrug of the shoulders, and it is all that his questioner deserves. So also there may well be those who give their minds to the study of Astronomy for its own sake, and for the sake of the intellectual, aesthetic, perhaps even moral, delights which it yields. Those who neither understand nor desire these delights are like the rustic who stands unimpressed before the beauty of an alpine landscape, and they will not relish any better the following words of the celebrated mathematician Henri Poincaré : " Why," he asked, " does the astronomer persist in a tedious and irksome task, spending long night-watches in conditions absolutely devoid of comfort ? " And he replies, " It is certainly not any notion of large emoluments which induces him to it ; if any of you has that idea, it shows that he has never looked into the estimates for Public Education. No, if the astronomer works uncomplainingly, it is in order that he may share in a grand work which must needs exalt the human soul, bring it nearer to God, and at the same time make it more self-reliant. Though it must often be that he sees no more than a corner of the heavens, yet he feels that he is himself made greater thereby. That is what he gets as the wages of his prolonged toil." ¹

¹ Address delivered to the Société astronomique de France, on February 26, 1912.

I quite realise, however, that language like this is expressive of a subjective appreciation, and cannot be understood by numbers of minds whose bent is in another direction ; to them some other kind of arguments must be produced to prove the use of Astronomy.

Let them consider merely the interdependence of the whole body of our knowledge, which cannot be cut up into chunks each of which is entirely separate from the others. Although to a superficial mind entomology seems to have nothing in common with, for example, hydraulics or electricity, yet the compartments of human learning are far from being isolated by water-tight partitions, and the student of Nature soon discovers that causes are so linked together therein that we cannot even approach to the explanation of the smallest phenomenon without the assistance of the most varied branches of science.

I suppose that when primitive men contemplated the heavens and sought to tear from them their secrets, they had not to wait long before experiencing that vague feeling of the dependence, I may even say the relationship, which binds our mental acquisitions together. The recurrence of the same celestial phenomena day after day, year after year, soon compelled them to seek for a means of measuring time. Astronomy must have been the first of the sciences.

Later, it was seen that the determining of the position which they occupied on the Earth's surface was necessarily bound up with the shape of this planet which we inhabit ; since then, however, we have been considerably taken aback to find that this apparently simple question of the coördinates—of terrestrial longitudes and latitudes—poses modern science with a host of problems that were quite unsuspected in earlier centuries.

If Astronomy were an unprofitable and trifling study, unprofitable also would be Geodesy and its practical applications. Useless, too, must have been the discovery of the velocity of light by the help of Jupiter's satellites—

that wonderful achievement to which in former times explorers and seamen were so greatly indebted.

I know, of course, that we now possess a better method for determining the equation of light than the original one of Römer ; but this does not alter the fact that our physicists owe the discovery to a purely astronomical phenomenon. It is not easy to see, at the outset, what use there can be in fixing, within a few metres, the position of the Observatory at Washington with respect to the one at Paris ; yet, when we have obtained a closer approximation to the value of longitudes and latitudes, we have—without intending it—contributed to the progress of science in the most diverse fields. It may be that I shall surprise more than one of my readers when I assert that the successful accomplishment of such a task has widened the horizons of our knowledge in regard to the mechanism of rotation of the terrestrial globe, to the movements of the spheroidal shell, to the internal density, to the tides of the interior and their possible relations with seismology, and finally to the laws which seem to be connected with meteorology and of which the cause must in the last resort be related to that solar activity whose variations are studied by astronomers.

This concatenation of the smallest facts of the Universe that are accessible to our senses, often only after they have been magnified by our instruments, has never been brought out more clearly than by the discovery of spectrum analysis. Starting as a mere astronomical experiment, when Kirchhoff was trying to enumerate the substances burning in the Sun, spectroscopy has since invaded the domains of all the natural sciences ; the physicist as well as the physiologist, the engineer no less than the student working in his laboratory, the scientist trying to solve the mystery of the constitution of matter and the chemist engaged in the search for new elements—all these must have recourse to the information which it furnishes. In the spectral rays, multiplied to an indefinite extent, they

all know that they will find the most disconcerting, and at the same time the most fascinating, answers to their questions. Let no one cry out upon the uselessness of our efforts when we direct our powerful telescopes, equipped with networks of fine wires, upon the thousands of stellar points that sparkle in the vault of heaven. Celestial chemistry has added to our knowledge of the chemistry of the Earth, and has put us in the way to discover the laws of inorganic evolution sooner than any laboratory experiment.

Who could have guessed, a quarter of a century ago, that helium, a substance unknown to our chemists and discovered first of all in the Sun, would one day be isolated by a Ramsay in experiments which will for ever be famous, would throw new light on radio-activity and so on the original differentiation of the chemical elements, and would at length enable us to find a substitute for hydrogen to the immense benefit of the science of aviation ?

The disposition, in our modern times, to go on branding as sterile the researches of Kepler and Newton, and the labours in Celestial Mechanics of such men as Poinsot, Clairaut, d'Alembert, Laplace, Le Verrier and Tisserand, would be a proof of extraordinary blindness, or at least of an obstinate shortness of sight. And if this may be said about Astronomy, a similar remark applies to every other branch of science ; some day or another, ideas which seem to be of the most speculative kind will come to be extended into the region of practical application, with material benefits to mankind which it would be hard to exaggerate.

No educated man ought to remain unacquainted with the progress of thought. You will say that there is not time enough to take up all these questions ? It may be so ; and it is for that very reason that this series of books has been projected, summarising the present position in the different branches of study.

The time for such an enterprise has never been so opportune. In days when the most firmly established

principles of science seem to be undergoing a formidable assault from the side of the scientists themselves, it is of the first necessity that we should examine the sum total of our gains, strike a balance, and take stock of our possessions, anxious not so much to discard our postulates as to recognise them for what they are. In the field of those sciences which depend upon observation, it becomes more than ever to-day the business of the scholar to overhaul his knowledge, and above all to verify the facts on which our theories and hypotheses have been built up. In Astronomy, more particularly, the development of photographic methods and the ever-increasing use of spectroscopic investigation, have already held more than one surprise in store for us. What information can we derive from these new modes of procedure?

The Earth on which we dwell forms part of a system which has the Sun for its centre. Like the other planets which are subject to its attraction, the Earth, while rotating upon its own axis, describes a closed orbit around that central star. But whereas these planets—Mercury, Venus, the Earth, Mars, Jupiter, Saturn, Uranus and Neptune—revolve in very nearly the same plane, this is by no means the case with the comets, whose orbits, which are often extremely elongated, are accomplished in planes inclined at the most varied angles to that one in which the planets in general circulate. Where do these bodies come from, with their puzzling behaviour? Are they strangers which started out from neighbouring systems and have been thrust upon our path? Or do they, on the contrary, accompany our Sun on its journey through endless space?

For it is one of the achievements of the science of our own day to have established beyond doubt that the Sun is not at rest among the fantastic multitude of stars. These bodies, which the ancients regarded as fixed, are perpetually in motion, and we might compare them as a whole with the molecules of a gas, moving each with its own velocity within some closed surface. To the enclosed space corresponds, for us, the entire Universe, with its

suns of all ages and sizes ; with its congested regions and its partial voids, which give rise to the most curious appearances in the vault of heaven.

What place do we occupy in relation to this mighty whole ? Relatively to the stars, we are moving ; in this gaping void some power is urging or drawing us onwards, and that at a speed fifteen times as great as the muzzle-velocity of a projectile fired from our biggest guns. Where are we going to ? For a long time the Milky Way seemed to be the limit of our Universe, but to-day we are driven to think that certain nebulae do not belong to it ; they may be separate universes, fragments of a mass of immeasurable extent, or rather islands belonging to some archipelago immersed in a shoreless ocean.

These are some of the troublesome problems whose solutions we shall have to discuss. The solutions—and there must be no mistake about it—cannot be other than provisional ; but that does not matter, for in the course of our investigations we shall reap an ample harvest. “ The celestial world,” said Tisserand, “ gets larger every day. It is a far cry from the heaven of Ptolemy to that which was revealed to us by the telescopes of Herschel, and photography discloses to us a still more imposing spectacle. Yet our curiosity is inexhaustible ; and however splendid may be the heaven which we are permitted to contemplate, we want to attain to greater knowledge still. We strive to realise what it was like in the most distant past, and what it will become in the most distant future. In this way—so it seems to us—our mind takes its revenge upon the shortness of our span of life and the frailty of our existence.”¹

¹ Address at the inauguration of the statue of Le Verrier, on June 27, 1889.



FIG. I.—CHART OF A PORTION OF THE MILKY WAY
(From a photograph)

ASTRONOMY TO-DAY

CHAPTER I

WHAT IS THE SUN ?

OF all the stars which people the immensity of space and sparkle in the firmament, there is none of which it concerns us more to have a thorough knowledge than the Sun.

A mere star amongst innumerable sisters, the Sun is, like them, endowed with a movement of its own, the speed of which, according to recent calculations, is about a dozen miles a second. Like the stars, too, our Sun has passed through different phases ; it has been evolving ever since the time when it was like the thousands of nebulae which telescopes have brought within the range of our vision, and shone with a diffused glow. The laws of condensation, which are studied by the science of cosmogony, have gradually brought it to the condition in which we see it to-day ; and in the millions of years which are still ahead, it will have to pass through new stages and will slowly advance along the road that leads to death, for the sky is full of worn-out stars whose vital throbbings are gradually growing feebler until they roll at last, dark and cold, through stellar space.

While, therefore, the study of our own globe teaches us about the evolution of the planets which, like the Earth, revolve around that focus of light and heat which we call the Sun, a knowledge of our central luminary itself provides valuable information as to the course of sidereal evolution. Such, in few words, is the justification for the preponderat-

ing position which has been assigned to solar studies during the last twenty years.

But the Sun has other claims upon our interest. In the microcosm of which we form a part—the solar system of which our orb of day is, so to say, the king—the Earth and all the rest of the planets are not only subject to its attraction but, in virtue of its pervading influence, they are affected by all its vicissitudes. To what extent are we dependent upon its variations? How does its condition influence the terrestrial phenomena which are recorded in our observatories? Such questions constitute the second problem with which solar studies confront us.

Before entering upon these questions, which would take us out from the region of pure speculation, let us briefly recall the leading facts which astronomers claim to be absolutely established in regard to this star which may be considered as our representative among the innumerable units of the sidereal army.

The Sun is a sphere whose volume is 1,300,000 times larger than that of the Earth, and is situated at a distance from us, in round numbers, of 92,800,000 miles. This enormous distance explains why the Sun, in spite of its size, looks to us no bigger than the full Moon. Its mass is revealed by its great power of attraction, although at the distance at which the Earth is situated this seems very slight, inasmuch as it causes our planet to deviate from a straight course by no more than one-ninth of an inch per second. The value of the solar mass, however, is 332,800 times as great as that of the Earth; reckoned in tons, it is expressed by the number 35 followed by 17 zeros; and in order to counteract the pull which it exerts upon our diminutive planet, it would be necessary to surround the latter with a network of steel wires as strong as ordinary telegraph wire, at a distance apart of only half-an-inch.

Observation of the solar disc has revealed the presence upon it of dark spots of a more or less permanent character; and these are regularly displaced in the same direction,

which for an observer looking at the Sun is from east to west. We conclude from this that the Sun possesses a movement of rotation similar to that of the Earth ; and taking account of our own motion round the Sun, which also takes place in the same direction of rotation, it has been calculated that the Sun turns completely round on its axis in twenty-five and a quarter days or thereabouts.

But at this point we come in sight of the puzzling circumstance that this rotation is not uniform. Carrington, by

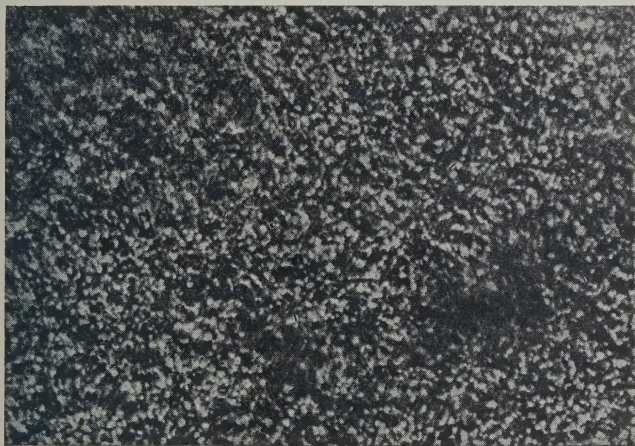


FIG. 2.—PHOTOGRAPH OF THE PHOTOSPHERE, SHOWING THE INCANDESCENT CLOUDS ON THE SUN'S SURFACE

admirable and patient work, has shown that the spots revolve more quickly according as they are situated nearer to the equator ; and this problem of the equatorial acceleration constitutes for solar physics its chief problem. We shall come back to it later ; but we perceive at once that the solar sphere cannot be entirely solid ; its surface, at the least, must be in a fluid state, either liquid or gaseous, otherwise it could not exhibit a characteristic of this kind.

An examination of the Sun through a telescope would

quickly put an end to any doubts which you might feel in your mind. With a high magnification, indeed, it is possible to distinguish on what seems to be the Sun's surface a kind of network, with meshes more or less crowded together; this is the photosphere, a radiant envelope whose appearance reminds one of a dappled, fleecy sky, a sky covered with cirrus. But in this case each cloud is of colossal dimensions; its diameter is 400 or 500 miles. It is true, however, that when they are examined carefully these "rice-grains," as they are called by those who have made a study of the Sun, break up into smaller "granules" moving rapidly in a comparatively dark environment of which hydrogen appears to be the dominating element.

It has inevitably seemed to astronomers, when observing these phenomena, that they had before them an atmosphere in which clouds were floating formed of materials that condensed at a certain definite elevation; and it was freely admitted that the photosphere owed its brilliance to the same process by which the mantle of a Welsbach burner becomes incandescent in the flame of a gas jet. Faye stated this view with greater precision: in the interior of the solar furnace, he supposed, all substances are resolved into their constituent elements; the gases or vapours rise up towards the surface, and when they have reached a certain level they form chemical combinations and thereby develop an amount of heat which is the same at all times. Such formations of glowing particles, either solid or liquid, are being precipitated every moment, and make up the woof, as it might be called, of the granulations of the photosphere.¹

Faye's ideas, which were put forward at a time when no one knew what the Sun's temperature was, must be considerably modified. The application of Stefan's law in physics has in fact made it possible for us to deduce from the rate of the solar radiation that the temperature of the photosphere must be between 7,000 and 8,000 degrees

¹ See H. FAYE: *Sur l'Origine du Monde*, Paris, Gauthier-Villars.

Centigrade. Such chemical combinations as we are familiar with in our laboratories could not even be imagined in such conditions, for at high temperatures like these all compound substances are resolved into their elements.

Unfortunately, too, spectrum analysis cannot help us here. The numerous black lines discovered by Kirchhoff in the solar spectrum do no more than bear witness to the presence of elements forming a gaseous layer above these clouds, whose mechanism and constitution we seek in vain to discover. This "reversing layer,"¹ which it has been found possible to observe directly during the all-too-brief periods of total eclipse, is somewhat ineffective in comparison, for its thickness amounts to scarcely more than 500 miles. It covers the photosphere in which the famous spots, already mentioned, have their origin. These usually start as dark points and get larger by degrees. One might think that there was a gap or a hole in the mass of clouds, but in reality there is nothing of the kind ; it is merely that the phenomenon of condensation is interrupted. As the spot increases in extent, a kind of halo, sharply defined around the dark nucleus, may be observed, and this is called the penumbra. A prolonged study of these formations is not needed to show that the streaked markings of the penumbra, converging towards the centre, are all formed simply by the clouds of the photosphere, which lengthen out as if through some kind of suction and disappear at their contact with the nucleus. By using the utmost care I have succeeded in observing these penumbral clouds almost up to the centre of the spot and at different levels.² The bottom layers, moreover, are at a low elevation, below the surrounding photosphere ; and recent researches, my own studies in particular, have shown that the spots cannot possibly be regarded as cavities.

¹ [When the light emanating from this layer is seen for a second or two during a total eclipse, its spectrum consists of a number of bright lines. At other times, however, its usual effect is to produce dark lines in the spectrum of the light which comes from the brighter photosphere behind it. Hence its name. TRANSLATOR.]

² See Th. MOREUX : *Contes Rendus*, March 6, 1904.

The substances burning in the spots are just the same as those observed in the reversing layer, and very probably the same as those in the photosphere. They are chiefly metallic gases of low atomic weight, such as iron, titanium, magnesium, chromium, cobalt, manganese, copper, zinc, aluminium, etc. Substances of atomic weight above 100 are not often observed; thus neither antimony, mercury

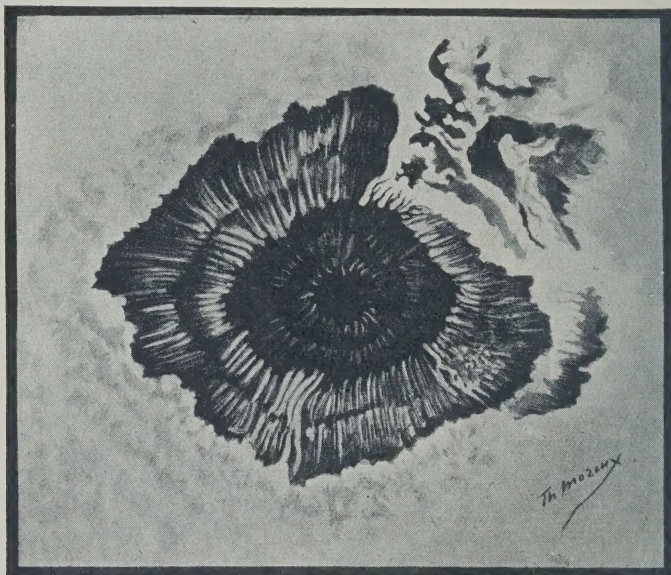


FIG. 3.—SUN-SPOT, SHOWING THAT THE ELONGATED CLOUDS OF THE PENUMBRA ARE FOUND EVEN IN THE NUCLEUS

(From a drawing by the Abbé Th. MOREUX)

nor bismuth is found. This rule, however, is not without exceptions, for the presence of lead has been established. Notice finally that hydrogen is present very largely, as are also carbon, helium and calcium.

The last two substances, together with hydrogen, seem to be the principal elements in another envelope, which is

situated above the reversing layer and is named the chromosphere on account of its rosy colour. This is the envelope which we perceive during the magnificent phenomenon of a total eclipse, and it is the region in which occur from time to time the phenomena known as "prominences." The chromosphere, indeed, seems even in its normal state to be unceasingly agitated by what look like luminous jets of flame crowded closely together, which Father Secchi compared to fields of corn in which the stalks were set waving by the wind; but in certain circumstances, and especially when sun-spots are to be seen on the solar sur-

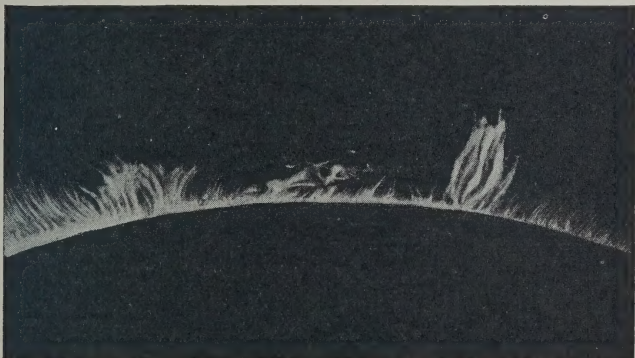


FIG. 4.—PHOTOGRAPH OF THE CHROMOSPHERE AND PROMINENCES, TAKEN DURING A TOTAL ECLIPSE

face, these outbursts attain to an extraordinary size. Prominences 50,000 miles in height are by no means rare, and in exceptional cases they are stated to attain to as much as 400,000 miles.

Thanks to an ingenious apparatus—the spectroheliograph—invented simultaneously by M. Deslandres in France and by Professor Hale in America, we are now able to obtain a spectrogram of the entire surface of the Sun whenever we please. The results have demonstrated that the disturbances of the photosphere are felt far beyond

the reversing layer, for the chromosphere shows flaky granulations, called flocculi, which are in a state of incessant commotion.¹

Higher still, we meet a fourth envelope, whose luminosity is so faint that it fails to make any impression upon our

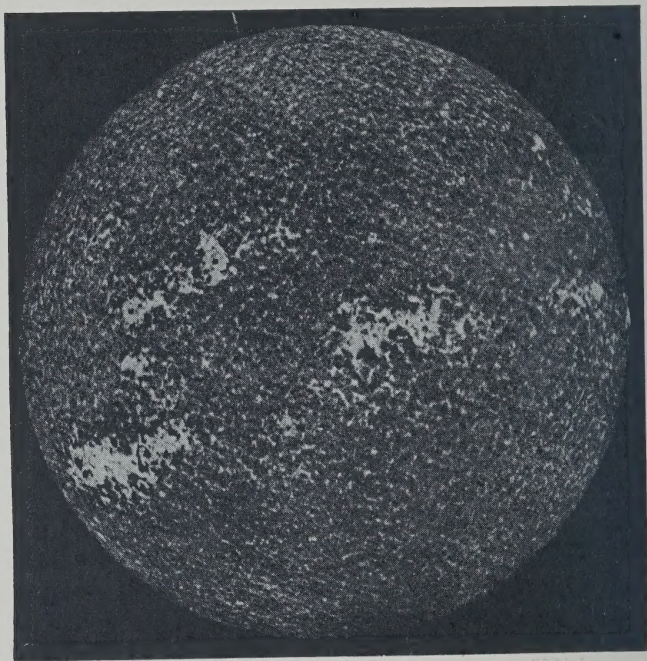


FIG. 5.—PHOTOGRAPH OF THE SUN TAKEN WITH THE SPECTRO-HELIOGRAPH
(Obtained by M. DESLANDRES at the Observatory of Meudon)

eyes, being veiled, as it were, at ordinary times by the brightness of our atmosphere ; it is easily visible, however, during total eclipses. This rarefied medium is called the corona. Scientists in the present day are very nearly

¹ See H. DESLANDRES: *Annuaire du Bureau des Longitudes*, 1909, *Resumé de Physique solaire*.



FIG. 6.—PHOTOGRAPHS, TAKEN WITH THE SPECTROHELIOGRAPH, OF THE PHOTOSPHERE AND THE LAYER ABOVE IT, SHOWING THE APPEARANCE OF A SUN-SPOT AT DIFFERENT LEVELS

agreed in the view that this luminous halo is constituted of extremely fine particles, which shine partly with their own light and partly by reflecting the light of the Sun. They form a kind of light powdery medium which reminds one of the matter forming a comet's tail. The spectro-scope shows the presence in it of a gas which is unknown on the earth, and to which the name " coronium " has been given.

There is no need to suppose, with the early astronomers, that these different solar envelopes are even relatively independent of one another ; on the contrary, they form

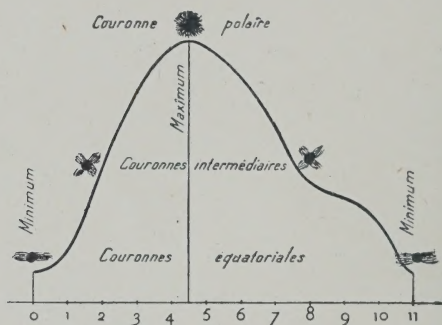


FIG. 7.—CURVE SHOWING THE VARIATION OF SUN-SPOTS AND OF THE SHAPE OF THE CORONA, OVER A PERIOD OF ELEVEN YEARS

a complete and single whole, as is abundantly proved by the systematic variations which are observed to take place in them simultaneously.

It has almost become a commonplace nowadays to say that the phenomenon of the sun-spots shows a periodicity of about eleven years. If we base our conclusions on a long series of these periods, it becomes evident that the number of spots, or rather the area of the solar surface which is occupied by the spots, goes on increasing for four and a half years and then decreases slowly for the next six and a half years. In the course of this eleven years period, the spots group themselves in different regions of the solar

globe in accordance with a law originally suggested by Spoerer ; in the years of maximum appearance they spread out over a larger zone, while they congregate near the Sun's equator in the years of minimum. Now this activity in the photosphere meets us again in the chromosphere with the very same fluctuations, for the prominences increase or diminish in the same proportions as the spots. The corona itself changes shape periodically ; when the sun-spots are at a maximum, the long and luminous appendages which compose it stretch out round the Sun like the four sails of a wind-mill ; but as the minimal phase approaches, the coronal rays seem to bend down towards the equator, and after the minimum has been

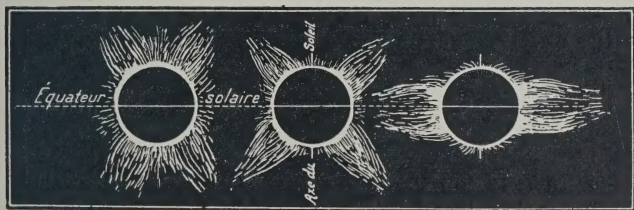


FIG. 8.—POLAR CORONA (AT THE MAXIMUM OF SOLAR ACTIVITY) ; INTERMEDIATE CORONA ; EQUATORIAL CORONA (AT THE MINIMUM)

passed this process is repeated in reverse order until the next maximum.¹

It is impossible to reconcile activity of such a kind as this with the old notion of a Sun which, without ever moving, poured forth on the Earth and the rest of the planets a constant amount of light and heat. We know numbers of stars in the sky which shine with variable intensity ; ought our Sun to be regarded as one of them ? Probably it ought to be, for the curves representing the fluctuations of these variable stars, to the study of which a special chapter will be devoted later, show characteristics similar to that of the Sun, namely, a rapid ascent followed

¹ See Th. MOREUX : *Les Éclipses*, chap. x. Fayard, Paris.

by a less steep decline which is not of uniform smoothness.

Had it not been for the phenomenon of sun-spots, it is very likely that this fact would have remained unnoticed. It is evident that the luminosity of the photospherical surface must itself be affected by variations, and at the sun-spot maximum we can easily detect an augmentation of the brightness of certain clouds of the photosphere which are well known by the name of faculae; but the surface as a whole is too bright for any variation in the total effect to be appreciable.

With regard to the emission of heat, however, the case is different. Attempts were made long ago to calculate the amount of the heat given out by the Sun, and it unfortunately occurred to the mind of Pouillet, who took up the question about the year 1837 at the same time as Sir John Herschel, to assign the name "solar constant" to the number of calories which the Sun transmits per minute to each square centimetre of the Earth's surface (assumed not to be protected by the atmosphere) upon which its rays fall perpendicularly. But the problem is not as simple as it seems at first sight, and it is the Earth's atmosphere from which the chief difficulty arises, for that absorbs part of the coveted energy.

Without entering into needless details, let us give at once the results which have recently been obtained by Langley and Abbot. The mean value of the determinations leads to our adopting for the solar constant a figure nearly equal to 2; that is to say, the heat of the Sun which falls normally upon a square centimetre every minute is sufficient to raise the temperature of two grammes of water by one degree (C.). But it must be repeated that this figure is no more than an average, and the calculations go to show more and more clearly what I suggested twenty years ago (see *Le Problème Solaire*),—that the thermal condition of the photosphere varies considerably, and in accordance with the increase or decrease of the sun-spots; in short, that what we have become accustomed to speak

of as the solar *constant* would be much more aptly described as the solar *inconstant*.

THE SUN'S INFLUENCE ON THE EARTH'S CLIMATE

As long ago as the year 1893, my attention was drawn to the possibility of a connexion between the thermal condition of the Sun and the fluctuations of our climate and weather.¹ Not that I was by any means the first to take up this question, for the ground had been cleared by an advanced-guard of pioneers, with Sir William Herschel among their number. At the same time, the subject was confused as a consequence of the assumption which was made by almost all astronomers, that sun-spots were cold regions of the photosphere—a paradoxical notion from which it followed that the greater the activity which the Sun exhibited, the less heat it produced. We shall see later how the facts ought to be interpreted ; but in any case, and apart from any particular theories, we are all agreed to-day that the heat of the solar envelopes varies, and that the period of the variation coincides with that of the spots and the prominences, the emission of heat being more pronounced when the Sun's activity is at a maximum.

It is therefore reasonable to ask whether this source of heat, of variable intensity, does not affect the temperatures which we experience on the Earth, and possibly all the other elements with which meteorology is concerned.

We may notice in passing that if in these circumstances the meteorologist does not have recourse to astronomy, he evacuates the facts which he is studying of all their meaning, and makes the problem of climatic variations an insoluble one.

The fact is that when the curve of terrestrial temperatures is drawn, it can easily be seen that during most of the time the periods of great activity in the Sun go along with high thermometric readings in a large number of

¹ TH. MOREUX : *Le Problème Solaire*, p. 281. Bertaux, Paris, 1900.

regions on the Earth. I am well aware that this fact may escape observation on account of the cooling produced by evaporation ; but nothing in nature is ever lost, and the Sun's energy will always be employed for some useful purpose. At the equator, as Koppen has shown, the mean temperature seems to be lower at the time of the maximum for sun-spots by reason of this evaporation,¹ though it is to be noted that the difference does not amount on the whole to as much as half a degree, and that statistics on

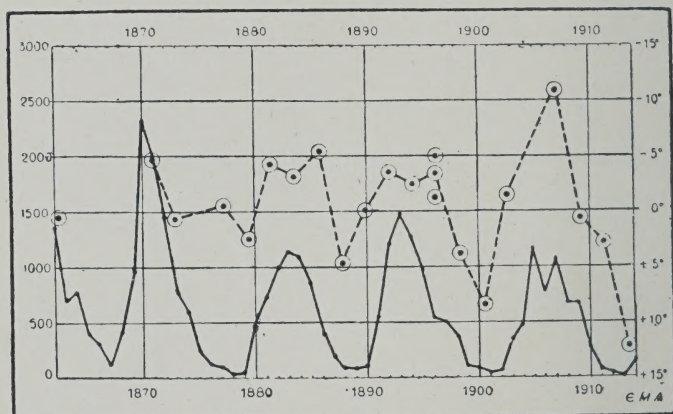


FIG. 9.—PARALLELISM OF THE CURVES REPRESENTING (BELOW) THE SUN'S ACTIVITY, AND (ABOVE) THE MELTING OF THE POLAR ICE-CAPS OF MARS

(E. ANTONIADI)

this point require very careful scrutiny. On the other hand, it certainly seems that in regions having a continental climate, the periods of great solar activity are more marked. In France, the yield of both corn and wine seems to be subject to fluctuations which bear a very close resemblance to those exhibited by the curve of the sun-spots, as I pointed out in 1901 ; and the parallelism between the two curves is still plainer if we take as the

¹ KOPPEN : *Zeitschrift für Meteorologie*, Vienna, t. viii, 1873.

basis of our comparison the corn-crop of the whole world for the years before the last world war had upset all results.¹

To take another example, we find this increased effect of the calorific energy at the time of the maximum of sun-spots shown in a more striking way by some phenomena which have hitherto received little attention but which open out new horizons to our study. Quite recently my friend E. Antoniadi showed that a close relation holds between the curve of the sun-spots and the melting of the polar ice-caps on the planet Mars,² and simultaneously

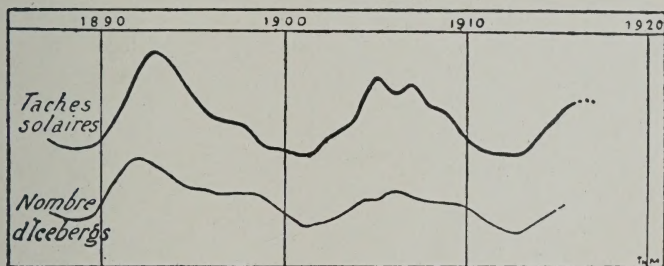


FIG. 10.—PARALLELISM OF THE CURVES REPRESENTING (1) THE SOLAR ACTIVITY AS EXHIBITED BY SPOTS, AND (2) THE NUMBER OF ICEBERGS ADRIFT IN THE ATLANTIC

(Th. MOREUX)

I established a similar connexion between the variation of this same solar activity and the break-up of the northern ice-pack which determines the drift of icebergs in the Atlantic.³

Thus the general question which we are considering seems to be settled decisively; at the same time, the precise mechanism by which the influence is exerted still awaits discovery, and it must be admitted that here our successors will find themselves faced by an awkward problem. For the Earth is a globe, three-quarters of

¹ Th. MOREUX: *La loi des grands écarts thermiques dans l'atmosphère*, "Cosmos," 1901, Nos. 835, 837, 839, 840.

² Cf. E. ANTONIADI, in *Revue du ciel*, December, 1916.

³ Cf. Th. MOREUX: *La véritable cause des gelées printanières*, "Petit Journal," May 9, 1914, and "Revue du ciel," May 1917.

which is thinly covered with water, and the remaining quarter, comprising the continents which emerge above the water surface, does not by any means present a symmetrical shape. If we remark further that our planet is enveloped by an atmosphere, and that while moving in its orbit it rotates about a sloping axis, it will be more easily realised how complex is the problem which the meteorologist has to deal with in attempting to link up the variations of our temperature with their cause in a variable Sun. This explains, too, why the laws of climatology are altogether different according as we are considering equatorial regions or zones of higher latitude.

If an example of this is desired, let us consider the distribution of rain on the Earth's surface. If the Sun is hotter when the spots are at a maximum, evaporation from the oceans will then take place more rapidly, and we ought to observe immediately afterwards a more abundant rainfall. Now what do we actually find? ¹

In 1874, Sir Norman Lockyer found in Ceylon, and afterwards in India, a rain-cycle corresponding to the eleven-year period for sun-spots; there were 5 or 6 dry years alternating with 6 or 5 wet ones. Similar conclusions were reached by Meldrum in the cases of Port Louis, Brisbane and Adelaide. In 1893, M. Gonzalez noticed the same thing at Bogota; he found that since the year 1610 periods of dryness were grouped round the minimal years of sun-spots, and on the other hand there were rainy periods around the maxima. The law seems to apply even to stations in higher latitudes—in places, that is to say, where the climate is not so regular as it is in tropical regions. It holds for the central part of France, as I showed in 1902; and in 54 stations examined in Great Britain, as well as in the 34 American stations for which a long series of observations is available, the same facts are found once more.

Nor does the Sun's influence stop there. In 1880,

¹ See, for this question, the volume in this series entitled, *Où en est la Météorologie*, by A. BERGET, pp. 278–297.

Chambers concluded from a very careful investigation that a relation exists between the variations of the spots and the barometric pressure, the rainfall, and the famines in western India.

Yet this eleven-year cycle, well defined as it is in different stations scattered over the whole of the globe, is not always to be observed in other regions. For example, in all the western part of Europe the periodic oscillations of the rainfall are much more complicated, and a clearly marked rhythmical variation can be shown to operate in a period of 33 or 35 years. Sir Norman Lockyer considers that the cause of this must be another solar cycle which is longer than the one of eleven years and is superposed upon it. I myself showed in 1903 that the climate of Paris, like that of the whole of the rest of France, is subject to a periodic oscillation the duration of which is, on the average, 35 years—17 years of dry weather followed by 17 years of wet; and this not only confirms the suggestion which Lockyer put forward from the astronomical side but also explains the empirical and somewhat mysterious rule in meteorology which has been known since 1890 as Brückner's law.¹ We need not go further into these considerations here. The reader who finds the question interesting on the agricultural or climatological side will find it discussed in my book dealing with the Sun and the forecasting of the weather.²

We have still by no means measured the full extent of the Sun's influence. Just as the photosphere seems to exert a direct effect upon the emission of heat, and thereby influences our climate, so the chromosphere, through those features which are themselves connected with the spots, acts as an electrical source which is always operating to alter the Earth's magnetic field. This introduces us to a chapter of what I have elsewhere called endogenous meteorology which up to the present has scarcely been

¹ E. BRÜCKNER : *Les oscillations du climat depuis 1700*, in "Geographische Abhandlungen," Vienna, 1890.

² Th. MOREUX : *Introduction à la Météorologie de l'avenir ; le Soleil et la prévision du temps*. Thomas, Paris, 1903.

investigated at all. It is not my desire here to outline even the shadow of a theory, and I will merely say for the sake of clearness that when large prominences occur, our magnetic needle seems to play the part of a detector of wireless telegraphy ; it is by its means that we learn about the electrical outbursts which have their origin in the Sun.

The abnormal deviations of the compass needle have long been familiar, but we needed all the delicate exactness of modern recording instruments in this particular department of physics to make plain to us the part which the Sun plays in these perplexing phenomena. Since the researches of Sabine in 1851, however, the fact that the variations of the compass depend upon the solar activity has been placed beyond reasonable doubt ; indeed, the parallelism between the curves of the two phenomena is striking. Yet the explanation of the connexion is so far from being a simple matter that from the very first attempts have been made to deny it ; and even among the members of the French Académie des Sciences there is an astronomer—and one of the most famous—who has not hesitated to state that “ since the period of the sun-spots differs from that of the magnetic deviations, there is no connexion between the two phenomena.”¹ In the circumstances, Faye’s shortsightedness must be considered most unfortunate, and the facts which have been accumulated cannot but be cruelly disappointing to him.

At the time when certain spots are crossing the Sun’s central meridian, or when large prominences are blazing out in the chromosphere, not only does the phenomenon produce a deviation of the compass but also the general electrical condition of our atmosphere is affected. The northern or southern auroræ suddenly shine in the sky, and light up the regions round the poles ; powerful currents circulate in our telegraph wires, and sometimes interrupt telegraphic communication. During the latest solar periods numerous examples of these disturbances have been collected, and the fact cannot now be doubted ;

¹ H. FAYE, *Annuaire du Bureau des Longitudes*, 1878, p. 650.

the Sun acts on the Earth in the same way as a dynamo would act on a solenoid placed within the magnetic field.

Similarly the so-called earth currents, which circulate from east to west and cause the compass needle to point towards the magnetic north, are due to the Sun, and their alterations in intensity, as well as in direction, must be explained by reference to its electrical storms.

At the same time, if we deliberately enter upon this investigation, the physicist will be entitled to put some questions to us on subordinate matters. Is it the case that the Sun is the sole cause of earth currents? Has it not been known for a long time that there is some connexion between the origin of these currents and earthquakes? It would seem that we ought to draw a distinction, and say that only some of the currents are accounted for by the Sun's activity.

I have considered the matter carefully, and I find myself unable to accept that view. Is not the truth rather this—that earthquakes are themselves produced by the earth currents, and so by the Sun? This is the problem which I set myself to study in 1900, and since that time a large number of facts have led me to adopt the latter hypothesis.

At the outset my attention was drawn to the fact that solar disturbances occur simultaneously with instantaneous outbreaks of fire-damp. Usually these outbursts take place at the times of violent earthquakes, which themselves concur with abnormal earth currents.

Now it certainly seems that the days on which there are outbreaks of fire-damp are often easy to foretell. For some years past, I have tried to test this by sending telegrams to the Belgian Geological Society a few days beforehand. Foreseeing, as a result of my examination of the Sun, the disturbances which would occur in the solar atmosphere, I gave warning of magnetic perturbations which were associated with outbreaks of fire-damp and with earth currents. The results which have recently been published have been of an extremely satisfactory

character, and therefore there is nothing rash in the assertion that the Sun is the chief culprit. Unfortunately, however, we are so poorly equipped, especially in France, for studying the Sun by the newest methods that no progress has since been made with the inquiry.

We know, indeed, that when a spot arrives by rotation at the Sun's central meridian, it does not of necessity give rise to a magnetic disturbance or to abnormal earth currents. Some spots are active in this way, others are not ; and I showed long ago that the solar activity is not necessarily associated with the spots, but may be linked up with other phenomena of a more or less tangible kind, such as prominences, disturbances in the Sun's higher atmosphere, and so on.¹ All these must be studied if we are to discover from time to time some connexion between the Sun and the phenomena occurring on our Earth.

From this it follows that it is childish to wish to connect up the occurrence of an earthquake with a particular sun-spot, as an effect with its cause. I do not think that we shall ever reach the point of being able to predict phenomena of this kind within a day. In the course of its rotation upon its axis, the Sun brings regions of undoubted electrical activity into positions opposite to the Earth, as we often assert ; but we are occasionally mistaken as to the reality of the event, or at least as to its significance.

I therefore tried to find out whether any relation existed between the principal periods of solar activity and the periods of earthquakes and of eruptions. In the case of the latter, the connexion is no longer in doubt.

Since 1610, when a beginning was made in the telescopic observation of sun-spots, it is true in general that volcanic eruptions coincide with the sun-spot minima ; in other words, volcanic activity increases in proportion as solar activity diminishes, and the more abrupt the decrease is of the second, the more rapid is the increase of the first.

¹ TH. MOREUX : *Le Soleil et le magnétisme terrestre*, "Cosmos," 1903, Nos. 616, 648, 680.

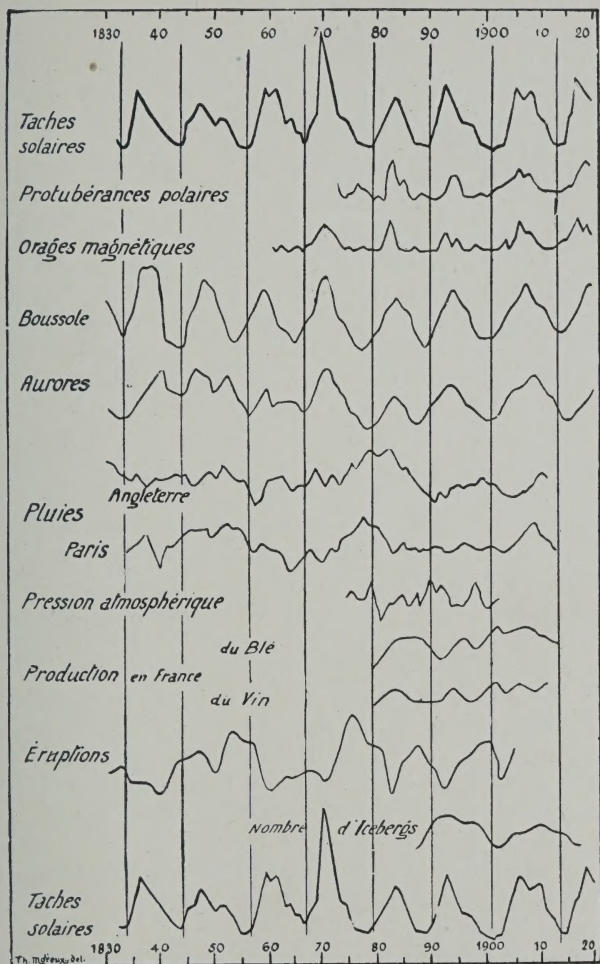


FIG. II.—DIAGRAM SHOWING THE CLOSE CONNEXION WHICH HAS BEEN ESTABLISHED BETWEEN THE SUN'S ACTIVITY AND CERTAIN TERRESTRIAL PHENOMENA OF A SPECIALLY CLIMATOLOGICAL CHARACTER

(Th. MOREUX)

As regards earthquakes, these take place especially at times when the Sun's activity is changing from an increasing to a decreasing process, or *vice-versa*. In this case the phenomenon does not easily lend itself to representation by means of a simple curve, for the Sun's activity itself presents sudden irregularities from day to day. At the same time, it is, as I have proved, at the end of the third year after the maximum, and during the year which follows, that earthquakes occur most often and with the greatest intensity. If greater precision than this is desired for our predictions, it can be achieved only through a careful observation of the Sun's actual condition at every stage by direct examination.

It was by means of these laws, and by such examination, that I was enabled to predict the great earthquake at San Francisco (in the *New York Herald*), and the more recent ones which ruined Messina and wasted Provence, as well as the terrible disaster of 1923.¹

These opinions which I first put forward in 1902,² and which the reader will find developed in my book on earthquakes, were regarded by a number of geologists as somewhat daring. "It is hard," they told me, "to see what connexion there can possibly be between electricity escaping from the Sun and upheavals of the Earth's crust." This is the sort of argument that one gets from theorists who deny the facts which they cannot explain! The history of science is full of it. When will scientists at length agree to look at facts, and the results of objective observation, before considering their own notions, their hypotheses, their theories—tottering erections which a breath of wind often destroys in a moment?

We must ourselves be careful not to lose sight of this warning in the inquiry upon which we are now about to enter,—the attempt to explain the facts which have been established. These theories about the Sun already in the year 1900 formed the subject of discussion of my first

¹ See my predictions in the *Revue du ciel*, January, 1923.

² See *Le Petit Temps*, October 12, 1902.

work, *Le Problème Solaire*. Since that time they have been developed, elaborated, extended in every direction. In order to study the Sun one needs to be at once astronomer, physicist, chemist, and mathematician. No single individual can suffice for such a colossal task ; he can only be guided by the general indications of science. But, after all, that is the surest way to avoid losing oneself in the maze which the study of nature presents to anyone who cherishes the laudable ambition of unravelling her mysteries.

SOLAR THEORIES

It would fill several volumes even to summarise the theories to which the study of the Sun has given rise. We can therefore do no more than glance at them here.

The energy of the solar furnace cannot be compared with that which is developed by our ordinary methods of combustion. A sun formed of materials like, for example, anthracite would last, in spite of its huge volume, for scarcely 5,000 years. Now it is a scientific fact that the Sun has warmed the Earth for millions of years ; geologists demand a hundred millions at the lowest estimate, in order to find room for the prolonged periods during which our globe has undergone its various transformations. Moreover, even if we admit that there has been a diminution of the Sun's calorific intensity as it has grown older, we are convinced by historical evidence that our climates have not varied for several thousand years.

There are, therefore, two things which have to be explained : (1) from what source the Sun has derived its enormous store of heat, (2) by what process it contrives to maintain the radiation which it sends us at a value which is very nearly constant or has at least been so over a long period.

Accepting the value which has already been given for the solar constant, one might suppose, as Mayer did some

time ago, that meteorites, continually falling into the Sun and bringing materials from outside, are sufficient to maintain the central fire. But this explanation only leads to the most absurd results. Let us consider a few figures :

The total amount of heat liberated by the Sun in space is 549,153,000 times as much as what we receive ; it would be enough to melt a block of ice as large as the Earth in a quarter of an hour ! To maintain the energy of this formidable source of heat at a constant value, we should be obliged, in accordance with modern theories, to allow for no less than 145 million tons of meteors falling on to the Sun every day. If this were actually happening, the Sun's mass would be continually increasing, and the immediate effect of this would be that our year would be shortened by three seconds, on the average, at every revolution. It is obvious that such a result would not have escaped the notice of astronomers.

Scientists like Helmholtz and Lord Kelvin have in vain attempted to improve this theory. By making use of the fact that the whole solar mass has contracted, the materials which are now concentrated having been originally diffused throughout a sphere that reached as far as Neptune, we can, perhaps, just manage to account for the Sun's possessing a quantity of calorific energy equal to fifty million times its yearly expenditure. But the conclusion would then be that the Sun had been shining for, at the most, fifty million years ; and we have already seen that geologists demand a far longer period than this.

Should we be any more successful if we took into consideration the reactions between chemical elements ? This, at any rate, was Faye's opinion, and a sketch of his views has already been given. It will be recalled that, according to this astronomer, there are produced, at the level of the photosphere, combinations of materials which in the interior are kept by the heat in an elementary state. The ascending movement, due to the heat below, brings these elements into the Sun's higher layers, where the less elevated temperatures make it possible for combinations

to take place. Theoretically, a satisfactory explanation is provided by this process of the constancy of the solar radiation, but practically it has to encounter objections of capital importance.

What compound substances are there which could originate in temperatures of 8,000 degrees ? The question is, indeed, all the more serious because, in order to provide for the Sun's incandescent brightness, Faye supposes the formation of solid particles like those to which the brightness of a gas flame or of an incandescent gas mantle is due. Then there is another contradiction involved : the compound substances which are formed in this way must plunge down again into the central mass, and be resolved afresh into their elements, but such a process cannot go on without a loss of heat ; the losses must be equal to the gains, and at this rate the reserve of heat would soon be exhausted. Finally, the expedient—for the theory is nothing more—collapses when we consider that the heat values which it would provide are far too small in view of the vastness of the Sun's radiation.

There is another method of explanation which has been resorted to, for example by Arrhenius. It is supposed that in the interior of the Sun there exist what are called endothermic bodies, resembling our explosives, which divide and decompose as soon as they are brought to the surface, setting free a large amount of heat. But even while himself adopting this new way of envisaging the process, M. Briner has shown that the gain which results from it is very slight ; the new theory is nothing more than an extremely precarious improvement upon the former one, and his conclusion is that " no manifestation of chemical affinity which is actually known to us will account for a liberation of energy which approximates even remotely to the amount required." ¹

Yet, in spite of all that has been said, the discussion of the problem has not been unproductive of results. It

¹ E. BRINER : *Le Problème de l'origine chimique du rayonnement solaire*, in " *Revue générale des Sciences*," May 15, 1916, p. 270.

has taught us that the reactions between atoms furnish a far greater number of units of heat than those due to formations which start from the molecule, which we are accustomed to look for in thermo-chemical tables. In consequence, we are convinced that the further we go in unravelling the constitution of matter, the more we shall find of unimagined reserves of energy.

It must, however, be frankly admitted that atomic reactions are at the best still far from satisfying the requirements of the problem. The maximum value is obtained in the case of the hydrogen atom, but even this is only 45,000 calories per gramme, while the figure which we require would have to be in the neighbourhood of 1,000 millions. But we now have, at any rate, a hint as to the path along which our inquiries should proceed.

The researches of such investigators as Becquerel, the Curies, Ramsay and Rutherford have taught us that the atom is not the ultimate material particle ; it ought rather to be considered as a complicated structure, a sort of solar system on a diminutive scale, with its planets revolving around a central sphere—electrons or corpuscles possessed of the most amazing velocities. Inorganic evolution, even though we may still be utterly ignorant of its laws, is no longer an empty word ; it is instead the “ simple body ” which has become a fiction, and matter has been disclosed to us in the very process of disintegration.

Astronomers had been the first to put forward these startling theories, for while the nebulae—worlds in their childhood, as they may be called—include only rare elements besides helium, hydrogen, etc., the suns which have already been formed are, according to their age, rich in new substances which have come into existence at the expense of the first. In the time of Kirchhoff it was supposed that every simple substance always yielded the same lines in its spectrum ; now, however, it is known that the number of these lines is by no means constant ; some of them disappear to be replaced by new ones if the temperature is raised from that of flames to that of

the electric arc or of the discontinuous spark. The pressure of the surrounding medium also plays its part in determining the result. It was by considerations of this kind that Crookes and Lockyer had been led to form the hypothesis of the existence of meta-elements and proto-metals long before the recent discoveries of radio-activity.¹

What conclusion is to be drawn from all these facts ? A single example will make the answer plain. Everyone knows that uranium is gradually changed into radium, and the latter into an emanation which is itself quickly transformed into helium.² At the same time, the rate of disintegration is very different in the different stages of the process ; while uranium takes 8,000 million years to evolve its successor in the series, the emanation completes its transformation in a few weeks, and radium occupies an intermediate position with an average life of about 2,500 years. Now in the course of this slow process, there is set free an enormous amount of energy. According to Professor Soddy, a kilogramme of oxide of uranium contains as much energy as 315 tons of coal ! The energy stored up in a ton of uranium would be sufficient to light the whole of London for a year. In changing into helium, the emanation liberates an amount of energy 3,600,000 times greater than that which results from exploding an equal volume of hydrogen and oxygen. Further, this energy does not appear only in the form of heat, but also as light, without reckoning the alpha, beta and gamma rays and other unknown forms of radiation.

Nor is this the characteristic of one series of substances alone. Everything disposes us to believe that there is not a single substance in existence which does not possess the radio-active property. The activity may be very slight or may even be masked altogether in the actual conditions in which the substances are found on the Earth's surface,

¹ Cf. Sir Norman LOCKYER : *Inorganic Evolution*, 1900.

² The account given above of the degradation of uranium should be read as a brief summary of the principal facts, not as a complete statement of all the stages of the process. [TRANSLATOR.]

but it is reasonable to suppose that in such powerful crucibles as the stars and the Sun it is greatly increased.

The presence in the photosphere of helium—a gas which is abundantly present in the Sun and yet is so sparsely distributed with us—goes to confirm these new views. Whether the interior of the Sun is in a gaseous or a liquid state or in the condition of a viscous gas, we shall in all likelihood never know, and it is not a matter of much importance; but we may suppose, with a high degree of probability, that in consequence of the great pressures, combined as they are with high temperatures, the chemical phenomena which take place there are subject to quite different laws from those which obtain in our laboratories, and that the process of formation of the common elements does not commence freely below the layers which are near the outermost boundary.¹ In such conditions, intra-atomic combinations and disintegrations must have free course; and it may well be imagined that the wastage of energy in the forms of the liberated heat, light and electricity, could go on for hundreds of millions of years.

All these facts were scarcely suspected, if indeed they were not entirely unknown, in 1900 when I published my book *Le Problème Solaire*. The discoveries in regard to radio-activity and transformation have modified my opinions in some respects, and my readers will pardon me if I take advantage of this opportunity to revise, and in particular to round off, my earliest hypotheses. At the present time there is no theory in existence to explain solar phenomena as a whole, but at least the attempt can be made to bring the known facts into relation with one another, and to point out the direction in which further investigations should proceed.

The Sun is a thermal machine which appears to us to be extremely complex; yet the complexity, surely, arises

¹ The mean density of the Sun is 1.4 times that of water. To counter-balance the lightness of the layers near the surface, the density of the interior must therefore, by reason of the pressure and in spite of the temperature, be enormous.

from our ignorance of the way in which the different forms of energy are connected with each other. It is for the physicists and chemists to clear the way into this vast region of research, but in the meantime let us try to form some idea of the possible mechanism of the processes which are going on in our huge star.

We have seen that by reason of the excessively high temperatures which exist in this gigantic crucible, the materials tend to make their way towards the surface ; the layers, therefore, which they traverse become less and less hot, and it is likely that a process of selection goes on at each different level, with the result that every substance is formed, or condensed as we may say, as soon as the thermal conditions allow it.

Certain metallic gases of a more refractory disposition—if I may be allowed the expression—such as hydrogen, carbon, calcium, etc., continue to ascend ; and it is these, along with helium which is produced by disintegration, that to a large extent compose the Sun's higher layers,—that is to say, the chromosphere, the prominences, and that layer which has been studied so thoroughly by M. Deslandres¹ and Professor Hale² by means of the spectroheliograph. Here, however, another phenomenon intervenes, which Maxwell foresaw in his electro-magnetic theory of light—the pressure due to radiation.

Fine particles of matter, whose diameters are less than a certain critical value, are repelled by a source of light ; that is to say, they are subject to a force of repulsion as well as to a force of attraction, and the former is the more powerful.

Since the famous experiments of Nichols and Lebedew³ this fact has been placed beyond doubt. Consequently we must suppose that above the very bright screen of the photosphere, the pressure of light begins to play an

¹ Cf. especially *Propriétés des couches supérieures de l'atmosphère solaire*, by H. DESLANDRES, *Contes Rendus* for 1912-14.

² Cf. G. HALE, *Study of Stellar evolution*, Chicago, 1908.

³ LEBEDEV : *Congrès de 1900*, t. ii, p. 133 ; NICHOLS and HULL, "Astrophysical Journal," 1903.

important part. Myriads of particles are projected outwards in jets which are more or less entangled with one another, and we have thus the explanation of the Sun's corona, with those streamers, sometimes straight and sometimes curved, which as we may note in passing are always associated with the Sun's period of activity.

We need not doubt that some of these particles reach the planets, and even go a long way beyond them. But the majority go to swell that mysterious ellipsoid known by the name of the zodiacal light, which is unquestionably

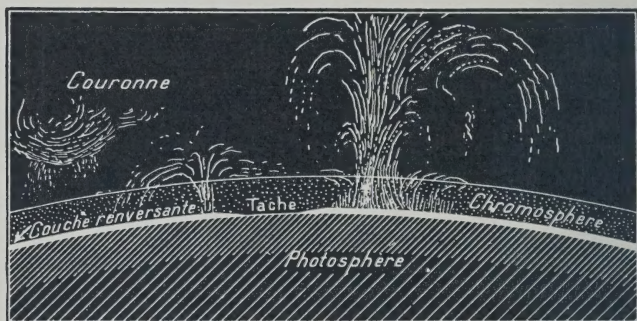


FIG. 12.—DIAGRAM REPRESENTING THE RELATIONS BETWEEN THE SPOTS, THE PROMINENCES, AND THE VARIOUS SOLAR ENVELOPES

a relic of the ancient nebula whose central part was occupied by our Sun.

I suggested some time ago that the successive condensations of the zodiacal light sufficed to explain the periodic law of the Sun's activity as well as that equatorial acceleration which has been demonstrated to hold for the bright surface of the solar globe. Recent facts, while they do not weaken my old theories, make it possible for us to penetrate further into this mysterious mechanism, and we shall return to the consideration of the question shortly.

However that may be, the particles thrust out by the pressure of radiation, after having gone to augment the

rings of zodiacal matter and to be incorporated with the corpuscles composing it, experience a gradual increase in their diameter, and so become the objects of the Sun's attraction. For some time they circulate round the central body in accordance with Kepler's laws, but in consequence of the resistances of the medium through which they move, they must end some day or other by falling back into the Sun.

This continuous rain of particles falls obliquely, since the rings tend to crowd more and more closely together. It will affect a zone whose extent in latitude will be greater or less according to the size of the annular belt. Such a penetration of the particles through the highest layers and their incorporation with the Sun is more than a mere theory born of the imagination, for what I only suspected when the first edition of *Le Problème Solaire*¹ was published has now been verified by recent researches. A vortex movement is generated in the mass of particles, and, meeting the chromosphere obliquely, they are engulfed in the photosphere, thus giving rise to the phenomenon of the spots.

This being so, we can understand that the spots are produced by a system of high pressures,—somewhat like our anticyclones on the Earth,—a system which operates to prevent the rise of the underlying gases. These gases would therefore be hotter than the surrounding mass of the photosphere, which would account for the suppression of a part of the radiation. Such is the basis of my hyper-thermic theory.

Around the spots, but further away than the penumbra, a zone of lower pressure would commence, which would be favourable to the outburst of the gases, and hence would arise the formation of prominences,—which is exactly what we have proved by observation to be the case.

After the beautiful experiments of Prof. Hale on the magnetic field due to the sun-spots,² an attempt has been

¹ Cf. *Le Problème Solaire*, p. 132 and fig. 32 ; see also p. 244 et seq.

² Cf. HALE : *Bull. Soc. astr. de France*, July 1916 and September 1919.

made to revive Faye's cyclone theory. As I have studied the Sun almost daily for more than twenty years, and have observed thousands of spots and followed their evolution, I shall, I think, be allowed to take part in the discussion with an expression of my own view.

While it is true, as Hale has demonstrated, that the layer



FIG. 13.—DETAILS OF A SUN-SPOT, MUCH ENLARGED
(From a drawing by the Abbé Th. MOREUX)

above the spots exhibits signs of vortex motion, thereby behaving in a way which I had foreseen in 1897, I nevertheless maintain the conclusions at which I arrived long ago. I am convinced that no spot shows cyclonic movement at first, but such movement when it arises is due to the intrusion of the photosphere into the spot, either from in front or from a region at the side. The process of pouring a thin stream of liquid into a larger mass of the same kind illus-

trates the mechanism which leads to the disappearance of every one of the spots on the Sun's surface. Moreover, the rotation may be in any direction whatever, and is not produced, as Faye had supposed, in the same way as in the cyclones of our atmosphere.

In consequence of the differences in the velocities of the clouds of the photosphere, those nearest the equator moving most rapidly, it used to be thought that there would be produced in that region something analogous to the vortices which are set up by friction in a fluid mass. Now, nothing of the kind occurs ; and in default of observation—which has been neglected on account of the time which it takes as well as on account of the difficulty and even danger that it involves—recourse might have been had to arguments based on analysis, and it is really extraordinary that no astronomer before me had conceived the idea, surely a very obvious one, of testing the fact by means of calculation.

Investigations with the spectroscope have simply confirmed the peculiar law of the Sun's rotation which Carrington had deduced from his observation of spots. If the spots actually come into existence as the result of differences of velocity which produce cyclonic conditions, it is quite evident that the phenomenon ought to exhibit its greatest intensity in that region in which the velocity-differences between two adjacent layers are most pronounced ; and such regions are shown by calculation to be situated in 35° of latitude, either north or south. On the other hand, we can consult the sun-spot statistics, and inquire what they tell us. They are found to give quite contrary indications ; the spots appear most of all in solar latitudes included between 10° and 20° on one side or other of the equator.¹

We are forced to conclude that the spots are not produced by the peculiarity of the Sun's rotation. Everything leads us to suppose that the phenomenon of the spots and the accelerated rotation of the equatorial zones are both pro-

¹ Cf. *Le Problème Solaire*, p. 196.

duced by one and the same cause, external to the photosphere. And this cause, as I have already indicated, is the falling into the Sun of the meteoric materials of the zodiacal light and of the corona, which are continually being maintained by the out-thrust of fine particles above the photosphere.

The mechanism of the process, too, is free from serious difficulty, since spectroscopic research, especially in the

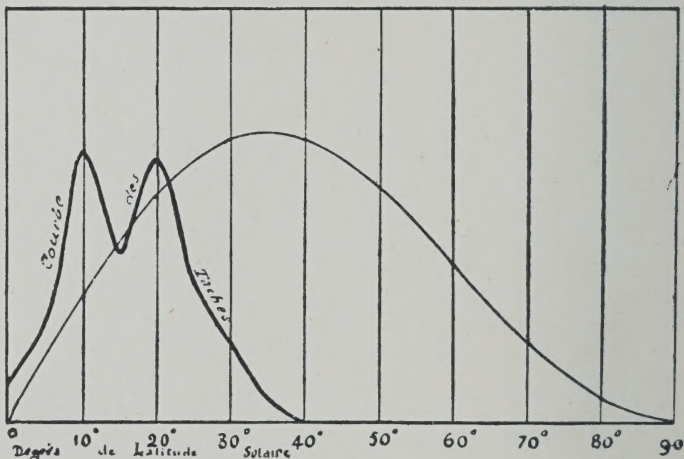


FIG. 14.—FIGURE TO SHOW THAT SUN-SPOTS CANNOT BE DUE TO VORTICES PRODUCED BY VELOCITY-DIFFERENCES

hands of Lewis Jewel, has succeeded in proving that the corona does not, like the underlying envelopes, rotate as a single whole. The materials composing it are endowed with velocities which are greater in proportion as they are closer to the photosphere. Except in so far as their motions are resisted by the surrounding medium, they conform to Kepler's laws, and—more remarkable still as a confirmation of the theory—it is in the equatorial part of the ring that the maximum velocities are attained.

Young had thought, in 1897, that this peculiarity of

the Sun's rotation was nothing but a survival from conditions long past, and that the velocities of different parts of the photosphere would soon become uniform; but recent measurements have demonstrated that the values of these velocities are subject to exactly the same periodic law which is manifested in all solar phenomena. This confirms once again the notion which we are compelled to form as to the intermittent character of the action of the meteoric rings upon the layers of the photosphere.

At this point, however, it must be frankly confessed that there is a gap in the theory. If the materials ejected by the Sun fall back into it, after however long a stay in the external corona or in the ellipsoid of the zodiacal light, and so give rise to periods of activity and of relative rest, it still remains for us to find a definite reason for the intermissions.

At one time I had recourse to the idea of an alternation of meteoric rings differing in density, and I supposed that they fell into the Sun successively over a period of eleven years; but I am not ashamed now to confess that the cause which I postulated, even if it be admitted as true in itself, seems from the mechanical point of view very far from adequate to the effects produced. We must look for the explanation elsewhere, and in doing so we find once more that the discoveries of radio-activity are opening out to us new and unsuspected horizons of what is possible.

In his exceedingly suggestive book *Radioactivity and Geology*, Professor Joly asks what the effect would be upon our globe if radium were present in it to the extent of two-billionths of the whole amount of matter; and he calculates that at the end of a hundred million years this small quantity of radium must have raised the temperature of the central core of the Earth by 1800° .¹ After this, there is nothing improbable in the supposition that a

¹ Cf. F. Soddy: *La Radioactivité et l'Évolution du monde*, in "Revue Scientifique," 1919, p. 549.

similar process must be taking place in the Sun. In any one of the lower layers, relatively near to the photosphere, even simple substances must, by reason of the high temperatures, be resolved into their elements ; and the accumulated energy due to their disintegration must mount up to a truly formidable value. Meanwhile the forces thrusting outwards are balanced by the downward pressures of the superincumbent masses, but this antagonism cannot remain indefinitely in a state of equilibrium. No doubt some of the materials are continually escaping outwards ; yet the gains of energy are always more than equal to the losses, and the lower the level the greater is the disproportion. At some particular moment, the covering shell becomes incapable of counterbalancing the internal pressure, and is burst through. The emission of fine particles must attain its greatest value at the time when the spots and prominences are at their maximum ; at that time, too, the whole of the Sun is affected, and the streamers of the corona invade even the poles of the solar globe. At the same time the rings of matter in process of condensation reach out to a far greater breadth than at the minimal period when they form no more than a belt round the equator. And as we have already indicated, the sun-spots, connected as they are with the descent of the materials originally ejected by the internal pressure, exhibit in regard to their latitudinal distribution a similar rhythmical variation, being crowded together close to the equator in the years of minimum activity exactly like the corona.

If these views are correct, we have here the long sought explanation of a problem which had come to be regarded as insoluble—the periodic activity not only of the Sun but also of those variable stars which figure on the pages of our star catalogues in rapidly increasing numbers ; and at the same time we have an inkling of the mechanism which produces the equatorial acceleration both of our Sun and of the planets like Jupiter and Saturn which we shall study in later chapters of this book.

May we not say also that we have a hint of the true explanation of those turbulent periods through which volcanic activity seems to have passed on our own globe at different stages of its geological development ? The history of the Earth makes it clear to us that the tertiary period was marked by a renewed outburst of volcanic fires. The internal energy which, in Europe for example, had been quiescent during almost the whole of the secondary period, awoke once more and revealed itself in outbreaks of the most resplendent character over the whole of the Earth's surface. It was then that a series of gigantic folds was reared up at the edge of the old northern continent from Spain to the eastern limits of India, comprising the Pyrenees, the Apennines, the Alps, and the mighty mass of the Himalayas.¹

The energy accumulated in the underlying layers of our globe in consequence of atomic disintegration would seem to explain not only that temperate heat which our polar regions enjoyed up to the time of the miocene period, but also that sudden change when the volcanic forces were roused to fresh activity as a result of the ever-increasing internal temperature, with the consequent upheaval of the Earth's already hardened crust, and the arrival of one of those glacial periods which always follow the belching forth of the hot gases from the eruptive centres. And continuing the investigation still further, we should be inclined to assent to the suggestion recently put forward by Professor Joly² that the different geological phases of the Earth were alternated with such states of incandescence.

These considerations shed new light upon all our ideas as to the evolution of worlds, whether we are considering some new star which, after being silent, dying, almost extinct on the confines of the Milky Way, suddenly kindles afresh and startles the heavens by its unexpected resurrection, or the planet in which the slumbering forces abruptly tear through the shroud which had been slowly

¹ Cf. TH. MOREUX : *D'où venons-nous ?* Paris, Bonne Presse, p. 99.

² JOLY : *Radioactivity and Geology*.

woven around it by the icy colds of space and the passage of accumulated thousands of years.

"Slow, irresistible, unceasing, unalterable,"—so wrote Professor Soddy a few years ago,—“so little in evidence that no generation before our own had ever discovered

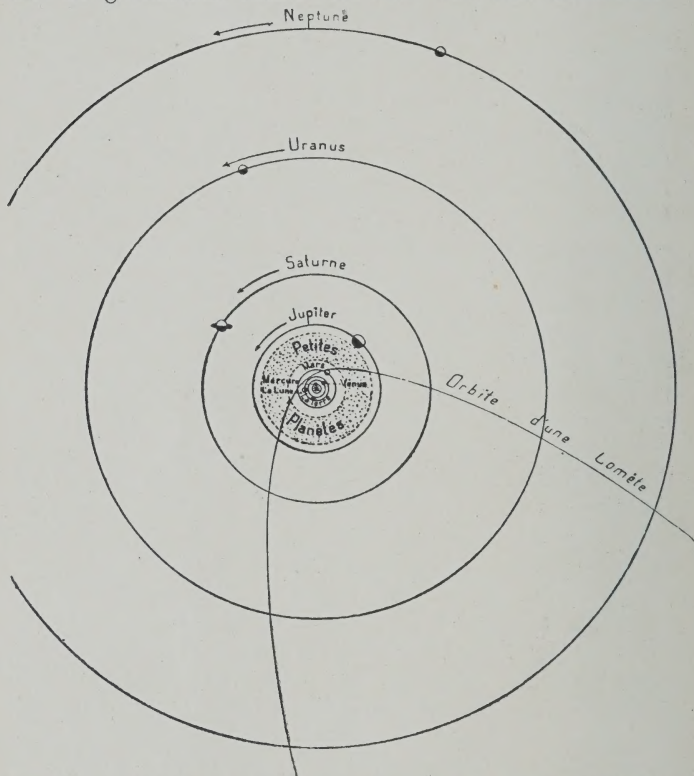


FIG. 15.—REPRESENTATION OF THE ORBITS OF THE PLANETS REVOLVING ROUND THE SUN, DRAWN TO SCALE (APPROXIMATELY 1 : 100,000,000,000,000)

their existence, the phenomena of radioactivity already appear, when considered on a vaster scale as regards both time and space, to be the ultimate causes of physical evolution.”¹

¹ F. SODDY, in “Revue Scientifique,” 1919, p. 548.

CHAPTER II

THE INTERIOR PLANETS

Mercury and Venus

TWO of the planets revolve around the Sun within the orbit of the Earth, and are therefore known as the interior planets. Of these, the one nearer to the Sun is Mercury, which completes its revolution in 88 days ; its orbit is much elongated, or, as astronomers would say, has a large eccentricity.¹ Its mean distance from the Sun, which is the length of its semi-major axis, is 35,935,000 miles ; and the fact that the radius of its orbit is so small is the reason why it is so difficult to observe it.

It is only just after sunset or before sunrise that Mercury can be perceived at all, for at other times it is lost in the light of the Sun. It was well known to the ancients, but they called it by two different names—Apollo in the morning, and Mercury in the evening.

In our cloudy skies it is necessary to watch carefully if one is to catch sight of Mercury on the horizon. Its angular distance from the Sun, called its elongation, may attain to as much as 28 degrees, and in a clear sky its appearance is that of a star of the first magnitude.

¹ It is a deduction from Newton's law of gravitation that bodies which revolve around the Sun must describe curves called conic sections ; that is to say, the path must be either a circle, an ellipse, a parabola or a hyperbola. In point of fact, the planets describe ellipses of greater or less eccentricity. It may be as well to mention that by the eccentricity of an ellipse is meant the number which is obtained as the quotient when the distance separating the two foci is divided by the major axis. If the two foci approach one another, the ellipse tends to become a circle and the eccentricity tends towards zero ; an example of this is the orbit of the planet Venus, of which the eccentricity has the small value 0.0068. On the other hand, when the ellipse is elongated, the eccentricity tends towards unity, as in the case of Halley's comet for which the value is 0.96.

All the biographers of Copernicus tell us that that great pioneer was never able to observe this planet; but Mr. Denning states that the story must be an invention, for he himself, living in England, has actually seen it not less than 150 times since 1868.

When seen through a telescope, Mercury exhibits phases like Venus and the Moon, and spots are seen on its surface. Many astronomers who have observed these spots during the last two centuries have claimed to deduce from them the period of this small world's rotation. A small world it certainly is, for its diameter is only 2,800 miles, or about 640 miles longer than that of the Moon.

In the year 1800, Schroeter, observing that in one of its phases the sharpness of the southern horn was blunted, deduced that the period of Mercury's rotation was approximately 24 hours 4 minutes. In 1801, Harding watched the progress of a dark spot in the southern hemisphere, and calculated by this means that the period was 24 hrs. 5 mins. 30 secs. Later observations made by the same astronomer led him to prefer the value 24 hrs. 0 mins. 50 secs. Bessel obtained a period 3 seconds longer than this by making use of the observations of Schroeter extending over an interval of 14 months. In 1882, at Bristol, Denning considered that a period of something like 25 hours was most in accord with the observed phenomena.

But in 1890 Schiaparelli, under the clear skies of Italy, arrived at results which completely upset all previous calculations, for he came to the conclusion that the planet rotated upon its axis in a period of 88 days, which is exactly equal to the time which it takes to revolve round the Sun. Since then, however, other observers have renewed the assertion that the period is in the neighbourhood of 24 hours, and at the present time the question is still unsettled.

In physical astronomy there is a spectroscopic method—the Doppler-Fizeau method, of which we shall have more to say when we come to treat of the stars—which makes it possible for us to calculate the velocity of a source of light

which is moving in the direct line of sight of the observer. By applying this method to the edges of a star, it becomes possible in certain cases for us to evaluate the velocity of its rotation.

Interesting results have been obtained by this means in the case of the Sun and of certain planets, but its application in the case of Mercury is a matter of great delicacy, partly on account of the difficulty involved in observing



FIG. 16.—VIEW OF MERCURY AS SEEN THROUGH A TELESCOPE
(From a drawing by the Abbé Th. MOREUX)

the planet itself, and partly on account of the small value of the displacement which has to be measured. We shall therefore have to wait until the method has been perfected still further before it can be used to decide this question.

All the planets perform their journeys round the Sun in the same direction as the Earth, and in planes which are nearly coincident with our own. Mercury is the planet whose orbital plane is furthest removed from the Earth's; it makes an angle of 7 degrees with the latter, and almost coincides with the equatorial plane of the Sun; nevertheless, in the course of the movements of our system,

it happens sometimes that the planet passes in front of the Sun, as seen from the Earth, and it then appears as a tiny black spot tracing out a line upon the solar disc. These transits can be calculated, and the next ones will take place on November 8, 1927, and November 12, 1940.

The transits have considerable importance from the astronomical point of view, for they give us information about the planet's diameter and also about its movement. At the same time, they raise more than one problem for us to solve. The following is a typical example :

Almost all the observers who have made a study of these transits, as Schroeter and Harding in 1799, de Plantade in 1726, and Moll, Prosperin, Flaugergues, etc., on more recent occasions, have noted the presence of a luminous halo encompassing the black disc, and this has appeared to them to be an atmosphere by which the planet is surrounded. Some of them have also remarked a glittering point of light upon the black spot. As regards the size of this margin, however, the results of their observations are not in agreement, and in November 1907 I took the opportunity afforded by a transit of Mercury to test the accuracy of my predecessors' observations. I may add that I had determined in the circumstances to summon a number of fellow-workers equipped with different instruments. All of us repeatedly saw the famous aureole, as well as the bright point, but it is interesting to note that we disagreed as to the times at which these phenomena were visible, and in the same way the size and colour of the margin were different according to the diameter of the object-glass employed. Shortly afterwards some experiments were carried out on artificial discs, and these enabled me to clear up the mystery. The phenomenon turns out to be subjective, and merely the result of an optical illusion.¹

The application of spectral analysis to the solution of this problem of Mercury's atmosphere has led to no conclusive result, and photometric investigations, which assign to the planet's surface a rather weak reflecting power

¹ *Contes Rendus de l'Académie*, Nov. 18, 1907, Note by Th. MOREUX.

or albedo,¹ lead us to the belief that Mercury is a world provided with scarcely any atmosphere at all.

But even if it be the case that some atmospheric covering exists to protect it from the Sun's radiation, we shall see that climatic conditions on the planet are by no means suitable for living creatures. The Sun, as seen from Mercury, appears as an enormous globe seven times bigger than its appearance as seen from the Earth. According to Stefan's law,² the surface of a planet turned towards the Sun must attain, at the distance at which Mercury revolves, to a temperature of something like 200 degrees above zero. This, too, is only the mean value. We have already seen that the orbit of the planet is a decidedly elongated ellipse, and the consequence of this is that twice in every Mercurial year—at intervals, that is to say, of 44 days—there are two well-defined seasons which are due solely to variations in its distance from the central luminary. These variations reach as much as 7,500,000 miles on each side of the average figure, and taking account of this we get a value of about 240 degrees for the temperature of the planet during its "summer." Sulphur and tin are therefore in a perpetual state of fusion.

Further, if Schiaparelli is correct in his conclusion that the planet always turns the same part of its surface towards the Sun, as the Moon does towards the Earth, there is no alternation of day and night to moderate the pitiless intensity of the solar heat. In such conditions it can be calculated that the temperature may even reach as much as 400 degrees, which is higher than the melting point of bismuth and lead. In such a reeking oven no organisms could possibly exist.³

The uncertainty which attaches to all matters relating

¹ The surface brightness of a planet is called its *albedo*; it represents the ratio which the light reflected by the non-luminous body bears to the whole of the light incident upon it.

² The law discovered in 1879 by Stefan at Vienna may be stated thus: the total radiation of an absolutely black body is proportional to the fourth power of its absolute temperature.

³ See Th. MOREUX: *Les autres mondes sont-ils habités?* pp. 44 et seq. Doin edition, Paris.

to the climatic conditions of Mercury is not the only one in which astronomers are involved in their investigations of the planet. To speak only from the point of view of celestial mechanics, there is one particularly troublesome problem raised by this small world.

All bodies which are subject to the Sun's attraction ought to obey Kepler's laws. Astronomers noticed, however, in the seventeenth century that the transits of Mercury across the solar disc did not take place exactly

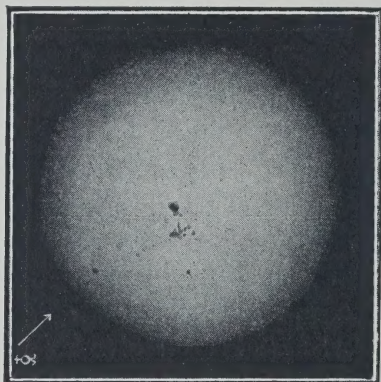


FIG. 17.—THE LAST TRANSIT OF MERCURY ACROSS THE SUN, IN
NOVEMBER 1907

(From a photograph by S. RAURICH)

in accordance with their predictions. There was an error of several hours in 1753, and one of three-quarters of an hour in 1786 ; and it seemed as if Moestlin was right when he said, in 1577, " This planet was formed in order that it might shatter the reputation of astronomers." At a later date Riccioli had written, to much the same effect, " No planet appears to move in such a complicated manner ; Mercury in the sky is as baffling to astronomers as mercury on the earth is to chemists."

Such an opinion would probably have still received a

good deal of support at the time when the learned geometer Le Verrier took up the question in the hope of throwing some light upon it. He knew very well that, in the practical working out of the movements of the planets around the Sun, it is necessary to take into account their mutual attractions; a body like Jupiter must needs exert some influence upon the movements of Mars or Saturn. It was essential, therefore, to determine with precision all the "perturbations" by which the path of Mercury was affected, and this was the formidable task which Le Verrier undertook to perform. He soon arrived at the conclusion that, in order to explain the undoubted digressions (involving an annual movement of perihelion amounting to $38''$), the mass of Venus must be taken as greater than its accepted value by ten per cent. But this was an impossible supposition, since an alteration would have to be made at the same time in the mass of the Earth; and to tamper with this figure was out of the question since, thanks to our satellite the Moon, it was known with great exactness.

There was, however, another possible solution—to suppose that the mass which was responsible for the disturbances was located between Mercury and the Sun. And thus the belief gradually arose in the existence of an intra-Mercurial planet. The elegance of this solution, however, did not make it the less risky. It was highly improbable that such a planet, which might perhaps be as large as Mercury itself, should have escaped observation. And if the existence of a group of asteroids were postulated instead of the unknown single planet, the same remark would still apply.

It was in vain that claims were made by various observers in the years which followed, that they had seen black points upon the solar disc; the last hope of any such discovery vanished with the progress of celestial photography, which definitely refused to record any intra-Mercurial planets during the fleeting moments of total eclipses.

From time to time some voice has been raised to suggest that astronomers should seek for the desired explanation in a different direction. It has been conjectured that the alterations in the velocity of Encke's comet, when in the course of its revolution it passes near the Sun, might be due to the presence of a resisting medium. And does not Mercury itself revolve within the region of the zodiacal light? This, however, cannot be accepted as a possible solution; for if Mercury or Encke's comet were actually moving through a resisting medium—and even if the resistance of the medium itself varied—the results surely would be cumulative, so that in the long run large alterations would take place. Apart from this, too, we cannot but feel that, in the absence of any data, the hypothesis rests upon an extremely insecure foundation.

In the past the greatest mathematicians have wrestled with these problems without success; perhaps, however, we are now at last beginning to get on the track of their solution, as the result of the wonderful advances which have been made in physical science during recent years.

The fact is that our laws, including even those which seem to be the most securely established, are only approximations to the truth. For a long time physicists and chemists believed in the idea of mass; yet we know now that mass, far from representing the quantity of matter which a body contains, is really a function of its velocity. For example, a corpuscle whose mass is represented by unity when it is actually or nearly at rest, has its mass increased to 1.32 when it is moving with a speed of 140,000 miles per second; and the value is even increased more than threefold and becomes 3.16 when the speed is 185,000 miles per second which is nearly equal to the velocity of light.

The electro-magnetic theory of Maxwell is the only one capable of providing an ultimate explanation of phenomena of this kind, just as it explains that well-known law of the "pressure," as it is called, of radiation, acting in opposition to gravity, of which we spoke in connexion

with the Sun. All these new facts seem to be inconsistent with the old Newtonian law of attraction ; hence one of two things must follow—either Maxwell's conception is mistaken, or else, if it represents the truth, Newton's law is not exact.

Nor are they only new facts which point in this direction. Ever since the time of Ampère and Faraday, physicists have been aware of a disagreement between certain electrical phenomena and the theory of gravitation. The discord was accentuated as a result of the researches of Maxwell, Max Abraham, Sir J. J. Thomson, Lorenz, and all the investigators who have built up the physical theory of the electron.

At the present time, therefore, everything suggests that in our explanations and our theories we should take account of motion and of its nature, even to the extent of introducing actual corrections into our results. Such, speaking broadly, is the principle of relativity, put forward by Lorenz as a hypothesis, and elevated to the rank of a definite theory by Einstein in 1905.

My readers must excuse my not entering here into details which presuppose an elaborate mathematical training ; to do so would be altogether inconsistent with my purpose. Questions of this kind do not lend themselves easily to popular treatment, and I must leave the results of the theory to speak for themselves. Once in possession of the principle of relativity, Einstein was not slow to push the consequences as far as possible, and proceeding from one conclusion to another he proved at last that it necessarily followed from the theory that the laws of gravitation are incorrectly stated.

The meaning of this should be clearly understood. Newton had said, " Things happen as if bodies attracted one another with a force directly proportional to their masses and inversely proportional to the square of the distance between them." But the fact is that this cannot be admitted as true unless we impose upon the law as thus enunciated a number of corrections which are indicated

by analysis ; by this means alone can it be made to square with Maxwell's theory, which has been abundantly confirmed by researches in both optics and electricity.

We now begin to see the full consequences of this reconstruction. If Newton's law is only an approximation, Kepler's laws which were analytically deduced from it can be no more than approximate too. And the result which we at length arrive at is this : we find that if, in the equations deduced from the Newtonian theory of attraction, we introduce the corrections required by the principle of relativity, we succeed in explaining those phenomena which gravitation by itself was powerless to account for, and the irregularities in the movement of Mercury are a mystery no longer.

Nevertheless, as no experimental proof of the theory was at first forthcoming, it was possible for its opponents to appeal to "fortunate coincidences." Now, however, it seems that a crucial test is available for us in more than one direction.

Einstein had proved, as a corollary to his theory, that if a ray of light passes near an enormous mass like that of the Sun, it does not travel in a straight line but must undergo a deviation ; in the case of a ray just touching the solar globe, this would amount to nearly two seconds of arc. The opportunity occurred of verifying this paradoxical result during the solar eclipse of May 29, 1919, which was visible in South America. The positions of the stars were determined beforehand with great accuracy, both with respect to the position of the Sun and relatively among themselves ; then photographs were taken during the period of totality, and the two sets of positions were compared. The result seemed at first to be in accordance with Einstein's prediction : the light had been bent exactly as was required by the principle of relativity.¹

Unfortunately, subsequent eclipses gave results of a

¹ See *The Observatory*, Nov. 1919 ; *Journal of the British Association*, Nov. 1919 ; *The Einstein Theory* ; *Bulletin de la Société astrophysique de France*, Dec. 1919.

much less definite character ; deflection of the light rays certainly occurs, but the law of deviation seems to be more complicated than the Einstein theory led one to expect. It is not possible, therefore, as yet to arrive at a confident decision.

As regards the application of the general principle of relativity to the displacement of the perihelion of Mercury, opinions are still much divided, and it is by no means certain that the value $43''$, which is furnished by the Einstein theory, exactly represents the quantity which Newtonian mechanics fails to explain. Some astronomers of repute, for example M. Esclangon, even hold that the problem has not been correctly formulated.¹ In this matter also an attitude of suspense therefore seems the right one to adopt, and we certainly cannot claim that the solution of the puzzle has been found.

Thus while the mass of Mercury is certainly between $\frac{1}{22}$ and $\frac{1}{24}$ of the Earth's, its precise value is still undetermined. On the other hand, the theory of perturbations has enabled us to fix with great accuracy the mass of Venus which after Mercury is the nearest planet to the central luminary.

With a diameter of just over 7,600 miles, which is only about 300 less than that of the Earth, and a mass equal to 0.817 of the Earth's mass, Venus is undoubtedly, of all the heavenly bodies known to us, the one which most nearly resembles our own globe. When to this is added the fact that the densities of Venus and of the Earth are nearly the same, we can understand why astronomers regard these two planets of the solar system as a pair of twin sisters.

On the other hand, because Venus is nearer to the Sun than we are, its mean distance being only 67,000,000 miles, it must receive twice as much heat as the Earth. Probably this fact provides the explanation of the appearance which the planet presents when seen through our telescopes. Its surface has, in fact, a reflecting power nearly five times

¹ Cf. E. ESCLANGON : *Les preuves astronomiques de la Relativité* (Gauthier-Villars, Paris, 1922).

as great as that of Mercury, and this would be impossible if what we saw were the solid surface of its globe. Consequently almost all astronomers who have made a study of Venus are agreed in admitting that what we perceive is only a layer of clouds floating in its atmosphere.

The existence of such an atmosphere has been otherwise proved by the appearance which is presented by the black disc of the planet at the moment when it begins to move across the Sun's face on the occasion of one of its rare transits. At such times the aureole becomes visible before the planet is entirely in front of the solar disc, and therefore the effect cannot be due to any subjective illusion as in the case of Mercury.

In consequence of this covering of clouds, the telescopic observation of this neighbour of ours is devoid of almost all interest. On its dazzlingly white surface, the eye can distinguish no detail; and in order to perceive a few fleeting shadows it is necessary to study it in daylight at a time when its brightness makes it visible to the naked eye. Yet the contemplation of the phases of Venus is not without its charms for the amateur astronomer. When the apparent angular diameter of the planet attains a value of 40 seconds, which happens between the times of its maximum elongation¹ and its inferior conjunction,² a magnification of no more than 55 diameters suffices to show it looking exactly like the Moon at the age of four days, and of precisely the same apparent size.

This same difficulty of detecting any characteristic details on the planet makes it extremely difficult to determine the period of its rotation. In 1666 and again in

¹ The elongation of an interior planet is the arc, reckoned in degrees, which separates it from the Sun.

² A planet is in conjunction with the Sun when they are both in the same position on the celestial sphere and are thus in a straight line with the Earth; the planet may be either between the Sun and the Earth, when the occurrence is called an inferior conjunction, or on the other side of the Sun, when it is a superior conjunction.

The planet is in opposition with the Sun when the Earth is in line between the two. This can happen only in the case of the exterior planets, that is to say those which move outside the Earth's orbit.

1667, J. Cassini announced a period of 23 hrs. 21 mins. ; but in 1726, Bianchini declared himself in favour of 24 days 8 hours. The latter astronomer carried on his observations in Rome and at Albano, and, not being at all embarrassed by the imperfections of his telescopes, he left us drawings of Venus enriched with an amount of detail which no one but himself had ever detected. It is even more amusing to notice that it is these very drawings of Bianchini which are still found in most of the modern astronomical text-books used in teaching !

All the astronomers who afterwards concerned themselves with this problem arrived at figures more or less like those of Cassini. But Schiaparelli, in a long paper in which he discussed all the observations which were known, showed no mercy towards his predecessors, and demonstrated for their benefit that the previous calculations were merely "the result of a series of fallacies and vicious circles." Taking up the question himself, he finally put forward a law for the rotation of Venus similar to the one which he had maintained in the case of Mercury : he considered that Venus rotated in about 225 days, which was the same time as the period of its revolution round the Sun. More recently, in 1921, Pickering thought he was justified in asserting that Venus rotated in a direct sense once in every 68 hours, the axis of rotation lying almost in the plane of the orbit.

Until these last results have been confirmed, nothing of importance can be stated with regard to the planet's climate. We only know this,—that at the distance at which Venus revolves round the Sun the mean temperature of the surface must be something like 85 degrees centigrade ; but even this is only a statement based on general theory. The temperature actually depends on the density of the atmosphere, and in any assigned region it is a function of the latitude and of the inclination of the planet's axis to the orbital plane, all of which are at present unknown.

But if we admit the truth of Schiaparelli's conclusions,

everything is changed. The hemisphere turned towards the Sun is then as hot as a furnace, while the opposite side must endure a climate enormously colder than that of our own polar regions.

Among the hitherto unsolved problems set us by this neighbour of ours, there is one which turns up periodically in the history of astronomy. When Venus is in inferior conjunction and passes between us and the Sun, its disc ought to be invisible like that of the new Moon, for the phases of the two bodies correspond. Now this is by no means always the case, and a large number of astronomers have seen the planet in this position, looking like a milky phosphorescent spot standing out against the darker background of the sky. Why is it thus visible?

All sorts of reasons have been suggested to account for the phenomenon, such as the luminosity of the oceans, if any exist on the planet; the phosphorescence of the atmosphere due to great heat; visibility by contrast, or by reason of the disc's being projected upon the background of the zodiacal light; illumination by lights like our aurora borealis, shining almost continuously; and so on. The best explanation still seems to be the theory of Arrhenius. We shall see later, when we discuss terrestrial magnetism, how this learned physicist conceives the Sun to exert its electrical influence upon the planets. The central luminary, he thinks, must bombard their atmospheres with electrified particles, and the intensity of these discharges must increase at times of abnormal solar activity.

There may well be a good deal of truth in this account, and if so we should have an explanation of the fact, known since the time of Hansky, that the degree of illumination of the dark side of Venus increases during the maximum period for sun-spots. It may, however, be noted in passing that there is nothing incompatible between the ideas of Arrhenius and the existence of aurorae on this neighbouring globe, since the cause which he postulates would itself at the same time produce more frequent

aurorae during the maximal years of solar activity, as we have already seen.

The conclusion with which we may fitly bring to an end this brief study of the two interior planets has doubtless been anticipated by those readers who have followed so far with attention ; it is that apart from the purely astronomical elements of Mercury and Venus, which we are continually getting to know with greater precision,



FIG. 18.—VIEW OF VENUS AS SEEN THROUGH A TELESCOPE
(From a drawing by the Abbé Th. MOREUX)

the physical conditions of these neighbouring worlds become ever more difficult to determine, in spite of our abundant resources in experimental methods of investigation.

Does this sound paradoxical and misleading ? Well, perhaps it is so ; yet after all, the case is just the same in all departments of thought. The further we advance in the study of nature, the more exacting we become ; and just because we are wiser than our predecessors, we begin to understand how complex are the phenomena which we

have to study. The different branches of science, too, are no longer regarded as independent of one another, at any rate to the extent that they used to be. Thus there is revealed to us more clearly the grand unity which binds together all phenomena ; and in the slow and relentless process of their evolution we see the working of a creative Mind which from the very beginning has conceived the Universe as a harmonious and ordered whole.

CHAPTER III

THE EARTH

IF the Earth is, with good reason, the best known of all the planets, it nevertheless provides astronomers with a number of most complicated and puzzling problems. It will be well, however, to commence this chapter with a statement of the astronomical data, about which there is no doubt at all.

We know, then, in the first place, that like all the other planets the Earth rotates on its axis in the *direct* sense ; this means that for an observer facing south the movement is from right to left, or from west to east. We have thus an explanation of the apparent movement of the heavens in the opposite or *retrograde* direction, the stars as well as the Sun and the Moon rising in the east and moving towards the west. This movement is the most uniform process that we are acquainted with, and we use it to regulate our timepieces and sidereal clocks ; so that if, when a star passes behind the central wire of the meridian telescope,¹ our clock does not show the exact time at which the event is due to take place, we conclude that it is either fast or slow, as the case may be.

Yet, if we look into the matter more closely, we find that our argument is a circular one. For our belief that the Earth moves uniformly is really an assumption, and one which is not borne out by theoretical reasoning. Since it was originally formed, the Earth has contracted ; and in that case, as we know from Mechanics, it must have

¹ It may be mentioned that the meridian telescope (or meridian circle, as it is usually called) is a telescope mounted in such a way that its optical axis cannot move out of the meridian plane, *i.e.*, the vertical plane pointing north and south.

increased the speed of the rotation ¹ which is accomplished at the present time in 24 sidereal hours. It is, at any rate, a fair supposition that the contraction must still be going on ; to what extent, then, is the rotation being accelerated at the present time ?

There is, however, another element in the problem. The Moon, by its action in producing the tides, checks the rotatory movement of our globe, and tends to make our day longer ; while at the same time this expenditure of lunar energy is bound to increase our satellite's distance from us. In some hundreds of millions of years, the Moon will be far more distant, and will have so retarded the Earth's spin that the terrestrial day and the lunar month will be of the same duration. Further, we have to take into our reckoning the meteors and fire-balls which fall on to the Earth's surface and increase its mass, thus counteracting the process of shrinkage.

The sum of the matter is that we can no longer claim to know definitely whether the forces tending to retard the Earth's rotation or those tending to accelerate it are the more powerful. Yet, in spite of this ignorance, we continue to regulate our clocks by a process which we pretend is uniform but which is assuredly nothing of the kind.

I know that considerations of a different sort can be advanced to show that the length of the day has not varied to any important extent since the time of Ptolemy, but none the less we shall do well to feel rather less confidence as to the validity of our conclusions.

And, indeed, the variation of which we are speaking can be proved to exist. For some years past, astronomers at Greenwich have been convinced that their clocks were not in absolute agreement with their observations, and the discrepancy was not a matter of a few thousandths of

¹ This follows from the proposition of equal areas. Since the angular momentum remains constant, the planet must rotate more quickly as its radius diminishes, in order that the areas described in equal times may still be equal.

a second, but of four or five seconds of sidereal time. As, however, the error recurred systematically and periodically, it was clear that it was not the clocks which were to blame, but the terrestrial globe itself, which in virtue of changes recurring every thirty or fifty years was responsible for the variations in the period of its rotation.

From what cause do these variations arise? The inquiry is going on continually, yet no one can discover the answer to the question. We may remark, however, in the first place that the magnitude of the fluctuations is found to vary with the degree of the solar activity, so that once again the Sun must be accounted the culprit. In what way would this action of the Sun take place? We will attempt an explanation, but before doing so a digression is necessary.

The latitude of a place, measured by its distance from the equator in terms of arc, used to be regarded as a constant. Great, therefore, was the surprise when the announcement was made several years ago that the positions of our observatories on the surface of the Earth appeared to be changing, and their latitudes were different year by year. An expedition was despatched to the Sandwich Islands, on the other side of the globe, to test the fact in the opposite hemisphere; the result was that exactly the same conclusions were reached, and from that time it has been established that the terrestrial pole alters its position on the surface of the globe. In other words, the Earth's axis of rotation is not fixed; the whole mass of the Earth turns round a succession of different axes which intersect the surface at different points. Let us hasten to add, however, that the displacements are extremely small, and have not, since the commencement of these observations, exceeded 0.6 of a second of arc, or roughly twenty yards; and the oscillation, complicated though it is, exhibits a periodic character.

Now I am convinced that in this phenomenon we are once more dealing with one of the Sun's misdeeds, and this opinion is held by many other astronomers. Suppose

that we could transport a mountain range like, for example, the Himalayas, to Greenland ; we should at once alter the centre of gravity of the Earth, and its equilibrium would be destroyed ; a rocking movement would immediately ensue, and we should witness a slight displacement of the pole.

Thus it would suffice, in order to produce a deviation of the Earth's axis, to move a heavy body on its surface, and it is possible to calculate quite precisely the work that would have to be done to effect the change. I have myself made such a calculation, and it is not difficult to show that in order to displace the terrestrial pole by about twenty yards we should need to employ something like 50,000 million horse-power for a year. That is a large figure, you say ? Quite so, but this amount of work can be done by the action of heat in producing evaporation from the oceans. The number of tons of water transported in this way from the equator to the north polar regions simply as a result of the evaporation produced by the Sun's heat can be estimated as, on an average, 700 million per annum. It can, therefore, easily be imagined that the irregular distribution of this quantity of water, when it condenses in the form of either rain, snow or ice, results in an irregular displacement of the terrestrial axis, and so in a disturbance of the regularity of the Earth's rotation.

To this cause might well be added another which no one so much as suspected a few years ago, and which I may call the Earth's respiration. Under the combined action of the Sun and the Moon, the crust of our globe swells out like the covering of a rubber balloon, and so behaves in exactly the same way as the water on its surface. Who could have thought there was so much elasticity in that rigid-seeming crust on which we live and feel so secure ?

In the year 1902, when I employed this notion of the Earth's surface elasticity to prove my theory of earthquakes, more than one seismologist received my suggestion with a certain amount of diffidence, with the exception of Professor Milne who was quite disposed to encourage me

in my view. But it is definitely known to-day that in spite of all the statements which have been made in the past, and in spite also of its being 40 or 50 miles thick, the crust of the Earth is so elastic that it is subjected every day to expansions and contractions which amount to at least as much as sixteen inches at the equator.¹

Thus, at a distance of 92,800,000 miles, the solar vibrations produce their effect on the tiny speck on which we

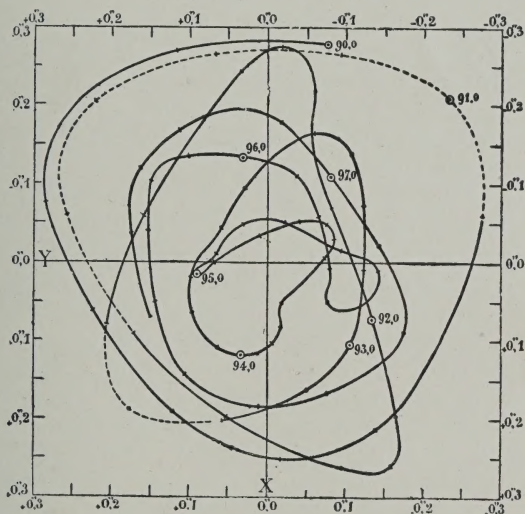


FIG. 19.—CURVE TRACED OUT IN THE POLAR REGION BY THE EXTREMITY OF THE EARTH'S AXIS, FROM 1890 TO 1898

are being whirled through space, while at the same time the Sun's attractive force compels the planets which are subject to its influence to describe curves of more or less circular shape.

The curved path which is described by the Earth has only a slight eccentricity at the present time, of the value

¹ See a note by M. LALLEMAND, *Les marées de l'écorce et l'élasticité du globe terrestre*, in "Annuaire du Bureau des Longitudes," 1910.

of $\frac{1}{60}$, or 0.0167. This value, however, varies, probably between the limits 0 and 0.07; so that our elliptic path, while preserving a constant direction for its major axis, becomes alternately more elongated and more nearly circular. But the period of the variation is by no means simple, and it can be shown by a process of calculation that the eccentricity of our orbit continues to diminish for 24,000 years and then increases for the next 40,000.

This journey which the Earth makes round the Sun, at an average speed of 18.48 miles per second, is very clearly revealed by the aberration of light,—a phenomenon which was accidentally discovered by Bradley at the beginning of the eighteenth century. It will be worth while to consider the explanation of the process.

If we are in a moving train during a shower of rain, the velocity of the vertically falling rain-drops is compounded with ours, with the result that they seem to fall in a slanting direction. In exactly the same way, if the Earth is moving, each ray of light which has come to us from a star must have its velocity compounded with that of the Earth. And in fact this is precisely what we find to be the case. The resulting deviation is very small; indeed, if we make a drawing to scale of the parallelogram of velocities, we shall see at once that one of the components represents 18.5 miles, or the distance along its orbit traversed by the Earth in one second, while the other is 10,000 times greater, since the velocity of light is about 185,000 miles per second. When the deviation is a maximum it amounts to not quite 21", and this is called the constant of aberration. As a consequence of this phenomenon, the star seems to trace out on the celestial sphere a small ellipse whose semi-major axis has exactly this value of 21 seconds of arc.

A more convincing proof of the Earth's movement could not be desired. At the same time, it should not be supposed that the phenomenon of aberration reproduces the irregularities of our motion. We are accustomed to say that the Moon revolves round the Earth, but taken

literally the statement is by no means exact. The Earth and the Moon really form a double system in space, revolving round its single centre of gravity, and this centre cannot possibly occupy the same position as the centre of the Earth. If we take account of the Moon's mass, which is 81 times less than ours, it is easy to see that the common centre of gravity of the two bodies does not, in fact, ever pass outside our globe ; it is at a depth of about 1,100 miles below the Earth's surface, and moreover it is itself continually changing its position. It is this point that we revolve around, once in each month. The same thing happens in the case of the whole solar system : when all the planets, including the imposing mass of Jupiter, are on the same side of the Sun, it can easily be seen that the centre of gravity of the Sun and that of the whole system cannot any longer coincide, and that sometimes the latter point may well be outside the solar globe altogether.

We must add that the planets in their turn, according to their changing positions, attract the earth in greater or less degree ; and the final result is that our orbit is very far from being a perfect ellipse, but is continually deformed by a number of perturbations.

It might be imagined that the Earth's revolution would at any rate be accomplished in a plane which preserved an unchanging position in space, but that is not the case. The plane of our orbit, which is of fundamental importance for us, and which is called the ecliptic for the reason that solar and lunar eclipses can occur only when our satellite is passing through it, oscillates continually, albeit slightly, about a mean position.

The number of these different movements has already mounted up to a respectable figure, but there are still two more to be added—the well-known ones of precession and nutation. Broadly speaking, the Earth's axis, which is inclined to the ecliptic at an angle of $23^{\circ} 27'$, remains parallel to itself throughout the course of our revolution round the Sun, and its direction determines the celestial pole. But the Earth is not a perfect sphere ;

there is a bulging at the equator ; and consequently the attractive force exerted by the Sun on this equatorial swelling is always tending to reduce the obliquity. The theorem of the composition of forces, however, when applied in this case, shows that no such result follows ; the obliquity is not altered on this account, but the Earth's axis moves slowly round so as to generate a complete cone in a period of 25,796 years, and with it of course the celestial pole moves round too. A good idea of the phenomenon is given by a top, when its axis of rotation traces out a cone around a vertical line.

In the same way the Moon, which does not revolve quite in the plane of the ecliptic,¹ ought theoretically to exert a similar attractive force on the bulging part at the equator, although its mass is less than that of the Sun. This does actually happen, and the resulting effect is called nutation. By reason of this lunar attraction, the extremity of the Earth's axis should trace out, in the region surrounding its mean position, a small ellipse whose major axis measures about 19 seconds, and the period of its description should be $18\frac{2}{3}$ years. It follows finally, from a combination of the two movements, that the extremity of the axis describes a sort of indented circle, which is completed about every 26,000 years.

To complicate the matter still further, it has to be observed that, in the case of both the Moon and the Earth, the centre of gravity does not by any means coincide with the geometrical centre ; hence it is probable that there are many other short-period nutations besides the one of which we have been speaking. It is no wonder, therefore, that from the point of view of Mechanics the description of the Earth-Moon system defies all the efforts of the most skilful mathematical analysis.

Thus, by a natural transition, we have been brought to the consideration of a subject which has inspired the

¹ The plane of the Moon's orbit makes an angle of $5^{\circ} 9'$ with the plane of the ecliptic.

efforts of geodesists ever since men first conceived the desire to know the real shape of the globe on which they lived and struggled.

When the statement is made in geography books that the Earth is an ellipsoid of revolution flattened at the poles, and then the difference is given between the polar and the equatorial radii, it seems to some people that there is nothing more to be said on the question. We are too much inclined to forget that science proceeds by means of successive approximations. The more perfect our

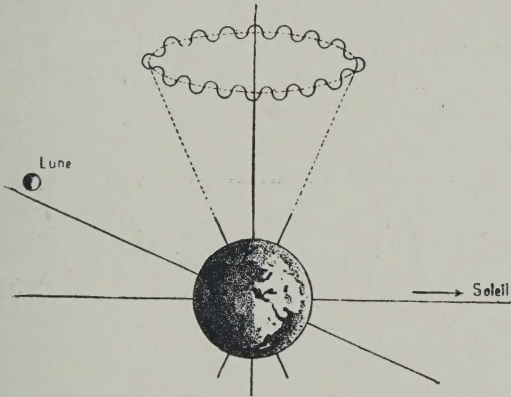


FIG. 20.—INDENTED CIRCULAR CONE GENERATED BY THE TERRESTRIAL AXIS IN 26,000 YEARS, UNDER THE COMBINED INFLUENCE OF THE MOON AND THE SUN

methods of measurement become, the farther are we bound to push our investigations. So the shape of the terrestrial globe seems to us at the present time to be far more complicated than it seemed to our predecessors. Even if we ignore the mountains and ocean beds, it is still quite out of the question to regard the geoid¹ as a regular solid.

¹ Geodesists call the Earth a geoid to express the fact that its shape cannot be defined by reference to any other solid. It is simply "earth-shaped," just as a pear can only be described as "pear-shaped."

[TRANSLATOR.]

We have at our disposal three distinct methods for obtaining an exact account of the irregularity. First, by means of complicated triangulations we can measure the lengths of meridian arcs in as many different places as possible. Secondly, there is a method which has already furnished valuable information, depending on the effect upon a pendulum of the variations in the force of gravity. And thirdly, we can obtain some help in the solution of the problem from a whole series of astronomical phenomena, such as precession, nutation, the irregularity of the movements of the Moon, and the occultations of stars. Each of the three methods assists the other two; but in the last resort we cannot dispense with the actual measurement of arcs, in order to obtain data from which we can start.

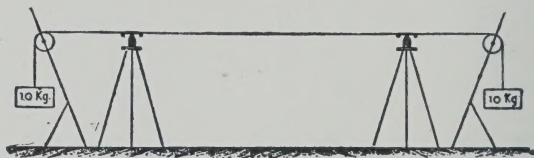


FIG. 21.—APPARATUS EMPLOYED IN THE MEASUREMENT OF BASE LINES BY MEANS OF THE INVARI WIRE

Now this process of measuring constitutes a lengthy operation, and one which bristles with difficulties. In former times Delambre and Méchain measured the base lines of their triangles simply by placing metal rods end to end; but we are no longer content with such methods. A new standard of accuracy was made possible by the discovery, in 1885, of a metal known as *invar*, an alloy of steel and nickel of which the expansion at ordinary temperatures is practically nil. By using a wire 24 metres long, stretched between two tripods, it is possible to proceed at the rate of nearly a mile a day; and whereas, at the beginning of the nineteenth century, the results obtained were liable to an error of nearly an inch in every mile, by the employment of the invar wire the error has been

reduced to only about one-tenth as much, and with the invar rod it has even been brought as low as $\frac{1}{2,500,000}$ of the measured length, or about one-fortieth of an inch to the mile.

Similar progress has been achieved in regard to the measurement of angles. Quite recently the error used to amount to 5 or 6 seconds, but the perfected theodolites which we now possess have reduced it to one-tenth or one-twelfth of this value.

The first result of working with the new processes was that the metre was found not to correspond exactly with its definition¹; it is 0.2 of a millimetre too small. This means that it is after all merely a conventional unit. But is this a thing to be regretted? I do not think so, for we shall see from what follows that the very idea which was in the minds of those who suggested the metre involved a mistake of principle.

At the present time the survey of the Earth has been carried out in all possible directions, and the results have made the problem only the more puzzling. It is found that, even between the same latitudes, meridian arcs are not all of equal lengths, and dissymmetry is everywhere; it becomes more pronounced still when the two hemispheres are compared; and the equator itself, instead of being accurately a circle, like the largest circle of a spheroid, has different radii of curvature at different longitudes.

This is a most unsatisfactory state of things for astronomers, for they are continually requiring, in their practical calculations, to make use of the mathematical elements of the terrestrial globe. It has therefore been found needful to try to determine average values which are not too far removed from the real ones. For the irregularly shaped geoid is substituted a nearly equivalent ellipsoid of revolution, which seems for the moment to serve fairly well in regard both to pendulum observations and to astronomical phenomena. The mean polar radius

¹ The metre was originally defined to be the ten-millionth part of the length of a meridian arc from the pole to the equator. [TRANSLATOR.]

is in this way taken as 3949·948 miles, while the equatorial radius exceeds this by 13·285 miles and has the value of 3963·233 miles. The polar compression is thus nearly $\frac{1}{298}$.¹

Geographers and geologists are not greatly interested in this merely approximate solution which is required for astronomical purposes. By considering the matter closely, they have found that certain systematic variations which occur in pendulum observations and in the value of gravity point more and more to the truth of an old theory which was long ignored. It was suggested by Green in 1875, but more than twenty years elapsed before it was revived.

According to this theory, the Earth would tend, in the process of cooling, to take the form of a tetrahedron or triangular pyramid, with four faces and four corners or coigns. The seas would occupy the depressions and form the faces of the pyramid, while the continents would be situated round the coigns and would reach out along the edges.

The facts seem to be in considerable agreement with this supposition. Three of the coigns are in the northern hemisphere; to use the picturesque expression of Suess, they are the Scandinavian, Canadian and Siberian "bucklers," the last being situated near Yakutsk. Moreover these projecting continents are of very ancient formation, and their ramifications extend more or less uninterruptedly as far as the South Pole. The opposite faces consist of the Southern Atlantic, the Indian and the Pacific Oceans. Lastly, the fourth corner forms the Antarctic continent, to which there corresponds, on the opposite face, the frozen Arctic Ocean.

On this hypothesis, it is easy to see that it would be a mistake to look for perfect symmetry either in the meridians of longitude or in the parallels of latitude. The tetrahedral theory accounts for the inequality of the polar radii, and at the same time gives a more satisfactory

¹ Like the eccentricity of an ellipse, the compression or ellipticity is a ratio. Its value is obtained by subtracting the minor axis from the major axis, and then dividing the remainder by the major axis.

explanation than any rival theory does of certain facts of astronomy which are inconsistent with the Earth's being a true ellipsoid of revolution. So, too, the general plan of the Earth's relief and the main lines of the fractures or crumplings on its surface would in this case be the logical consequences of a process of contraction which began during the earliest geological periods and has proceeded ever since in accordance with the same laws. I have, indeed, found it possible to construct on the basis of Green's idea a complete theory of volcanic activity, and those of my readers who are interested in the subject will find it fully worked out in my book on earthquakes.¹

My views are corroborated still further by those tidal movements of the Earth's crust of which we have spoken already; and though this chapter is concerned with the Earth, it will not be out of place to show how the electrical action of the Sun is capable, in the circumstances, of intervening either to check or to accelerate the phenomena associated with the contractive process.

No department of cosmical physics is more obscure than the electrical or magnetic action of the Sun upon the planets. Yet, as we have already observed, the parallelism which exists between the curves of solar activity, of the Earth's magnetism, and of the intensity and frequency of the polar aurorae puts the fact beyond doubt. The Sun certainly acts upon our planet in this way, even though the mechanism of its action has up to the present baffled our attempts at explanation.

The Earth behaves like an enormous magnet, yet we know that its inner core is really far too hot to possess any magnetic properties.² The direction of the magnetic needle must, therefore, be due to earth currents. What, then, is it that gives rise to these currents? The first idea which occurs to the mind is that they are induced by similar currents in the Sun; and it may be noted in passing that

¹ Th. MOREUX: *Les Tremblements de terre*, Jouve, Paris, 1909.

² See on this subject J. BOSLER: *Les Théories modernes du Soleil*, pp. 244 ff., Doin edition, Paris, 1910.

this would explain why our magnetic pole is not coincident with the geographical north pole, as a consequence of the fact that the axes of the Sun and the Earth are not parallel.¹ But this is only to put the difficulty further back, for recent measurements of the Sun's magnetic field and even of that due to the sun-spots, which have been carried out by Deslandres and Hale² have proved that the suggested cause is not adequate to the result.

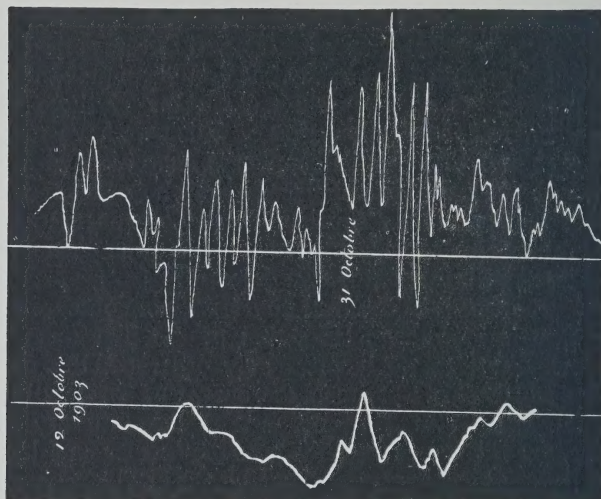


FIG. 22.—ABNORMAL DEVIATIONS OF THE MAGNETIC NEEDLE IN OCTOBER 1903, UNDER THE INFLUENCE OF SOLAR ACTIVITY

The problem is to account for an action the energy of which is capable of being transmitted across the 93 millions of miles which separate us from the central luminary. It would certainly seem that the action with which we are concerned must in such conditions be indirect. Now it is well known that the ionization of gases makes them con-

¹ See Th. MOREUX : *Le Problème Solaire*, Bertaux, Paris, 1900.

² See *Contes Rendus de l'Académie*, 1894 and subsequent years, *passim*.

ductors of electricity. In the opinion of Schuster, certain radiations emanating from the Sun, such as the ultra-violet rays of light, the Röntgen rays, and the radio-active emissions, might very well render the upper layers of our atmosphere electrically conducting, and so give rise to the recurring earth currents. Goldstein, Paulsen and Birke-land have suggested cathode rays ; Deslandres thinks that the chromosphere and the corona are in an especial degree the source of electrical influence, and is supported in this view by the scientists who have just been named. Ebert has invoked the Hertzian waves, and his idea has since been taken up by others—without, it must be admitted, any great success.

This being so, one might perhaps do worse than accept the theory of Arrhenius, who has recourse to the pressure due to radiation. We have already seen that there must escape from the Sun a multitude of particles which instead of being attracted to it are repelled by the solar light ; and this necessarily follows from the electro-magnetic theory of Maxwell. An unimaginable number of these particles must be ejected into space by the solar prominences, whose frequency is, as we have seen, connected with that of the sun-spots.

These corpuscles are the product of atomic disintegration, and so they consist for the most part of negatively electrified particles ; on reaching the Earth they impart their charge to the rarefied gases of the upper atmosphere. This charge, it might be supposed, would continuously increase the potential of the atmospheric layer in the same sense, and to an extent to which no limit could be assigned. But Arrhenius replies that this result need not be feared, for after a certain point the action of the solar light produces a diminishing effect. Thus the phenomenon of the aurorae might well be linked up with disturbances in the Sun. It is still more important to notice Arrhenius's calculation that a particle thus expelled from the Sun by the pressure of radiation would take about 45 hours to accomplish its journey to the Earth, and this is precisely

the length of time which appears to elapse between the occurrence of certain solar phenomena and the registration of their effects by our magnets.¹

Whether it be direct or indirect, the fact of the Sun's action upon the Earth cannot be disputed, and is more than a mere theory. The electric charge of the atmosphere is itself a variable quantity, and it is a remarkable fact that of all the phenomena which agree most closely in their variation with the periodic fluctuations of seismic activity, the closest agreement is shown by atmospheric electricity. This, therefore, it must be which acts as the intermediary between the Sun and our earthquakes, or—which comes to the same thing—between the Sun and the Earth's contractions.

Paradoxical as this statement may seem, I will try to show that it can be scientifically maintained. Everybody is acquainted with the Leyden jar, but it is not generally known that if the charge on the jar is altered, its volume is also altered proportionally. This can easily be verified experimentally by means of a spherical jar filled with acid. When a charge is imparted to the external coating of tin foil, the volume of the spherical vessel is enlarged, and the level of the liquid is seen to fall, the opposite effect being produced if the charge is diminished.

In the case of the Earth, the atmosphere plays the part of the tin foil on the outside, the terrestrial crust being a bad conductor takes the place of the glass of the vessel, and the internal coating of the jar is very well represented by the liquid or gaseous core of the Earth, which is composed of various metallic substances.

If, then, the electric charge resident in the atmosphere is by the Sun's action increased, we shall have a tendency to expansion in the crust, the lateral pressures will be more pronounced, and the shell will tend to support itself instead of pressing down upon the interior mass; hence there will be a cessation of earthquakes.

This is exactly what is found to be the case. Earth-

¹ See J. BOSLER : *op. cit. supra*, p. 314.

quakes are slight or do not occur at all in summer and in the afternoon, both of which are times when the electric charge has a high value. On the other hand, when the charge dwindles, as it does in winter or even in the latter part of the night, the shell tends to contract ; it is no longer independently supported, but weighs down upon the mass within ; the consequence of this is a process of settlement and collapse which involves earthquakes.

The same concomitant variation of the atmospheric electricity and of earthquakes is to be observed also in the annual curves and in those constructed to represent changes over a long period of time.

It is thus not difficult to understand that at certain times the gases enclosed within the crust try to escape in consequence of the pressure which it exerts upon them—a pressure which is itself due in part to the tendency to contract. The tension of the gases will go on increasing until the activity of the Sun has reached a maximum. And in this way we have an explanation of those relations between the two sets of phenomena which I established for the first time in 1900 and published in 1902.¹

As recently as in 1919 Fr. Marc Dechevens, of Jersey, demonstrated the existence of what is nothing less than a tidal fluctuation in magnetic phenomena. When the facts are better known, it will be interesting to see whether there is any remote connexion of the variations and recurrences of this tide with seismic phenomena on the one side, or with manifestations of solar activity on the other.

Whatever may ultimately be the fate of the theory which I have just outlined, the facts at any rate are indisputable, and it is facts which provide the most certain material of modern science. Our hypotheses are continually changing and becoming out of date ; as history shows, they are no more than a sort of *memoria technica*, which we can use to advantage doubtless, but only on the condition that we never mistake them for more than they really are.

¹ See *Le Petit Temps*, October 12, 1902, and also the diagram [Fig. 11] on page 21 of this book.

CHAPTER IV

THE MOON

WE now meet, for the first time in the solar system, the case of a planet which is itself attended by a secondary body revolving round it. I refer to the Earth, which has the Moon for its satellite.

Throughout the time when the two interior planets Mercury and Venus were being formed, the tides due to the Sun were probably experienced with great intensity; consequently, it is likely that the materials which might otherwise have coalesced to form their moons were carried away in the disturbances which these tides produced in the neighbourhood. We know little about the way in which the planetary system was formed, but it can be established that the number of the satellites of each planet increases with its distance from the Sun, until we pass beyond Saturn. The series begins with the Earth, the size of whose satellite is only one-fiftieth of its own. If, therefore, the Moon appears to us as large as the Sun, that is merely because it is so much nearer.

Like all the heavenly bodies, the Moon obeys Kepler's laws. It moves in an ellipse of which the Earth occupies the position of one focus, and the line which joins it to the Earth sweeps out equal areas in equal times. The eccentricity of its orbit, however, is considerable, being three times as large as that of the Earth's orbit, and on this account its distance varies greatly in the course of its revolution, which takes place in an interval of not quite a month. When it is in perigee, at that extremity of the major axis of its orbit which is nearest to us, it is rather less than 220,000 miles away; but its mean distance is about 238,000 miles.

Although it has been possible to determine the elements of the lunar orbit with very great precision, our satellite is still in some respects a Sphinx which baffles the intelligence of astronomers. The Moon is indeed the nearest of all the bodies by which we are surrounded, and it has been the most closely studied; none the less, its movements present a problem of alarming complexity. For in this case the question is no longer one of calculating, according to the laws of attraction, the positions of two moving bodies which attract one another according to Newton's law, but the Earth and the Moon together form a pair of objects which is itself acted upon by the Sun; and thus we are confronted by the famous "problem of three bodies" which has exercised the skill of so many mathematicians. The solution of the problem seems at first sight to be easy, and it was so regarded by the geometers of the eighteenth century; but the simplicity is only apparent, for as soon as it is examined more thoroughly the problem is found to depend upon the integration of a set of six differential equations, and there is no theoretical method for performing this operation.

In practice we proceed by successive approximations, and that no doubt explains why the discovery of the solution of the problem of three bodies, which was announced several years ago,¹ has so far led to no new result. In any case, the new method scarcely makes the calculation of the perturbations any simpler, and this calculation cannot be dispensed with for a complete understanding of the Moon's motion, since (in exactly the same way as the Earth) the Moon is 'pulled' not only by the Sun but also by the nearest planets Venus and Mars.

A further complication arises from the fact that the Moon does not move in the same plane as that in which the Earth revolves round the Sun, which we have called the ecliptic, but in a plane which is inclined to the latter at an average angle of $5^{\circ} 9'$; the Moon's path meets the

¹ By K. F. SUNDMANN, of Helsingfors, in 1913.

ecliptic twice in the course of each revolution, the two points of intersection being termed the ascending and descending nodes. The line joining the two nodes is not fixed, but has a retrograde movement, in consequence of which eclipses recur every eighteen or nineteen years. Nor is the major axis of the lunar orbit any more constant ; it revolves like the apsidal lines of the Earth and of the other planets.

All these particular complications in the satellites were explained by Newton and his successors. Mistakes, of course, were still made in the prediction of eclipses even in the last century, but it was possible to attribute this to other causes which did not depend upon the laws of attraction, such as a faulty evaluation of the diameters of the Sun and the Moon. So at least people reasoned in the time of Euler.

But this complacency did not last long, and the day came when Halley showed that the mean motion of the Moon was very different from that of the other heavenly bodies, in that instead of being uniform it was accelerated. Such a conclusion, it seemed, was demanded by the study of eclipses in ancient times. A century later, towards the year 1800, Laplace took up the problem and found a secular acceleration of $10''$; this was enormous, for those ten seconds meant that, apart from its regular progressive variation, the Moon's motion was augmented by this amount in *one* century, by $40''$ in two centuries, by $90''$ in three centuries, and so on, the first number being proportional to the *square* of the second. From this it followed that during the twenty centuries preceding our own time there had been a variation of $10''$ multiplied by the *square* of 20, or $4000''$, which is more than a degree ! And as the apparent diameter of the Moon measures about $32'$, or half a degree, the conclusion was reached that our satellite had been displaced in the sky to the extent of about twice its diameter. The result was all the more noteworthy because such a state of things announced very plainly that our satellite was getting nearer. If the secular

acceleration continued for a certain period longer, the Moon would end by falling on top of us.

Such a problem was bound to tempt the skill of so learned a mathematician, and Laplace proved that the phenomenon was really caused by a decrease in the eccentricity of the Earth's orbit, and was therefore subject to periodic variations. Moreover the 10" turns out to be too high a figure; it has since been determined by Stockwell as a little more than 8".¹

Even if we take account, however, of all the known perturbations, it is certain that the Moon's motion remains in part as inexplicable as ever, so that at the present time we are still unable to predict the Moon's *exact* position a long time in advance, and that is a matter of capital importance in relation to the calendar and eclipses. The revision of the theories of gravitation in accordance with the ideas of Einstein to which we have already referred, also seems inadequate to the task of supplying the solution of the puzzle.

Has this world, which is so near to us, revealed at least the secret of its physical constitution? That is the question which remains for our consideration. Observe that we are concerned here only with that half of the Moon's surface which is turned towards us, for the opposite side could never be seen by anyone. This fact is due to rather a strange cause. The length of the lunar month—the time which the Moon takes to revolve round the Earth—is precisely the same as the time which it takes to rotate. Suppose you hold a croquet ball at arm's length, and make your body rotate; when you have turned completely round, the ball will also have completed one rotation upon its own axis, although you have not released your hold of it, and it will have done so in exactly the same time as that in which it revolved around you. That is what happens in the case of our satellite; our attraction is exerted upon it so strongly that it moves round us as

¹ V. YOUNG, *Manual of Astronomy*, p. 300 (Ginn and Co., Boston, 1909).



FIG. 23.—PART OF THE MOON'S SURFACE, SHOWING THE APENNINES,
MOUNT CAUCASUS, AND THE ALPS
(From a photograph taken at the Paris Observatory)

if it were attached by a solid arm which prevented its having any separate movement of its own.

In spite of this, there is a narrow strip on both the east and west sides of the visible hemisphere which is revealed to us; owing to the fact that the lunar orbit is distinctly elliptic. This is the phenomenon which astronomers call the libration; to an observer on the Earth the Moon seems to oscillate slightly, first from right to left, and

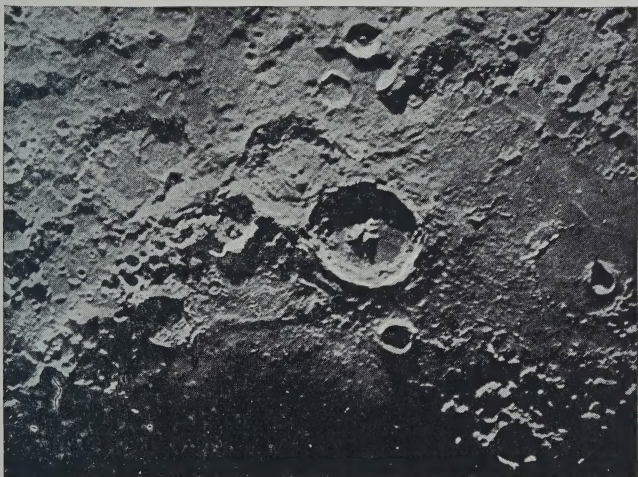


FIG. 24.—THREE LUNAR CIRCUSES: CATHARINA, CYRILLUS, AND THEOPHILUS

secondly from top to bottom since we see it sometimes above and sometimes below the ecliptic; and besides this there is a small libration due to our position on the Earth. The result, when all this is taken into account, is that instead of our seeing only one-half of the Moon, we are acquainted with 59 per cent. of the surface of this little world which attends us on our journey through space.

If you ever have an opportunity of looking at the Moon through a good telescope, do not fail to take it; you will

have, from the very first, a distinct impression of having been transported to a world which is in all respects unlike our own. Choose a day when the Moon is near one of its quarters, when the Sun is shining on it not directly but from the side, and the surface relief will be clear to you in all its splendour. You will certainly see there some large plains, which on account of their dark tints the early astronomers called *seas* ; but most of all you will be struck by the multitude of crater-formations which will remind you of the effects of volcanic activity on the Earth. These latter objects have all received the generic name of craters, but in some cases it would be much more appropriate to call them circuses. Moreover, they are far from being all alike, and in discussing them modern selenographers are forced to adopt some system of classification.¹

We find in the first place immense plains surrounded by ramparts of mountains—circuses with diameters ranging from 60 to 160 miles. A good example of this kind is the crater of Ptolemy, which is hexagonal in shape ; it measures not less than 115 miles across its longest diagonal, a distance equal to that from Paris to Havre.² So pronounced is the curvature of the Moon's surface—its radius being only 1,080 miles—that an observer situated at the centre of Ptolemy would not see a trace of the mountain wall which bounds the circus in all directions ; even the summit of a peak which rises to 8,800 feet from beyond the western horizon would be only just visible to him. There are some other circuses known to us which are still larger, such as Humboldt (130 miles across), Clavius (141 miles), Grimaldi, Stöfler, and lastly Maurolycus whose mean diameter is as much as 150 miles.

In this class we may also include the ring-mountains of somewhat less extent, with diameters varying from 12 to 75 miles, and with much smaller and lower walls. Originally these formations were probably a great deal

¹ For fuller details see Th. MOREUX, *Étude de la Lune*, Éditions Scientifica, Paris, 1913.

² Or from London to Bristol. [TRANSLATOR.]

larger than they are now ; they have been more or less completely demolished, and partly covered by the material which has formed the seas.

Quite a different aspect is presented to us by the very numerous class of crateriform circuses whose diameters range from 10 to 60 miles. In their case the interior is an enormous basin, the bottom of which is generally below the outside level. The walls are here replaced by piled-up mountains whose solid masses, in regard to both their size and height, are worthy to be compared with the Alps.

Such is the appearance of the famous Copernicus, with its ring-mountain forming a double boundary in which the highest summits rise to over 13,000 feet. In the

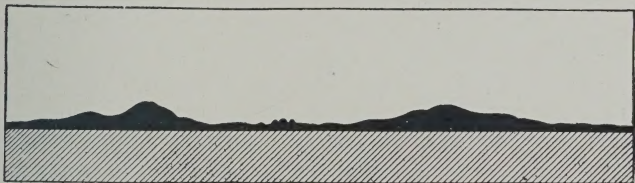


FIG. 25.—VERTICAL CROSS SECTION OF THE CRATER OF COPERNICUS

middle of the interior space spring up several sharp peaks which early selenographers regarded as so many outlets of volcanic eruption. Nasmyth even went so far as to construct, from this single case, a complete theory about these formations, which as we have said are extremely numerous on the surface of our satellite.

It is well known that on this near neighbour of ours, whose mass would need to be multiplied $81\frac{1}{2}$ times to equal that of the Earth, the value of gravity is one-sixth of what it is with us, and therefore the forces of eruption must be exerted there with an intensity to which we are quite unaccustomed. In these circumstances, Nasmyth said, the volcanic materials were distributed round the eruptive cones over circular areas of much wider extent.

But in truth, when the question is examined a little

more closely, it is not clear how the volcanoes could have been powerful enough to pile up around themselves, over a range of more than 30 miles, masses which are much greater than our Pyrenees and which rival the mighty Alps. Yet it is a childish mechanical theory of this kind that we find described in most popular books on Astronomy, and even in textbooks on the subject. It would seem as if in some cases science must have been a substitute for common sense.

Modern selenographers, however, do not relegate lunar volcanoes altogether to the realm of fancy. Craters there are, in great number ; the smallest are hardly more than half-a-mile in diameter, while the largest do not exceed 15 miles. Their inner sides are very steep, but outwardly they exhibit a gentle slope. A few of them are to be found everywhere, on the mountain ramparts as well as at the bottom of the valleys, on the summits of the mountains and on their flanks alike, often in the plains where they shine as isolated points of light betokening metallic streams which degenerate farther off into luminous trails that sometimes stretch right across the inside of the circuses. The ring-shaped wall is not always regular, and many are the crater-shaped shafts cut out as though by a punch. In some regions they are so close together that the appearance, to use Nasmyth's phrase, is like that of a heap of foam.

Mountain ranges, properly so called, are rare on the Moon, and further it must be remarked that they bear little resemblance to ours. Their most frequent characteristic is that of a titanic piling up of shapeless materials, out of which rise slender and pointed peaks like Cervin. Such is the appearance of the range of the Apennines, which is 400 miles long and 160 broad. The highest summits reach a height of nearly 20,000 feet. In the lunar Alps there are more than three thousand peaks, some of them rising to 12,000 feet above the level of the surrounding plain. These altitudes are exceeded in the Leibnitz and Dörfel Mountains, which rear themselves

up to a height of 26,000 feet ; the sharp peaks of the Rook Mountains, too, are 24,500 feet high.

When we compare these elevations with those of our highest summits, the disproportion is evident ; while the height of Mount Everest above sea-level is one seven-hundredth part of the Earth's radius, that of the lunar peaks which have been mentioned is the two-hundredth part of the Moon's. It is clear that the reason for this difference is to be found partly in the value of gravity which is only one-sixth of what it is with us, and partly also in the absence of those external forces of rain, wind and erosion, the effects of which were certainly checked on our satellite a long time ago.

At the present time, indeed, we are quite certain that if the Moon has any atmosphere it is so rarefied that it resembles at most the residue which is left by physicists when they have obtained the most perfect vacuum that they can achieve.¹ Consequently, in the plains and mountains of the Moon there is no air and no water, there are no winds and no storms. The rocks are detached noiselessly on the mountain sides, and roll down in silence to the ravines. If the volcanoes were not extinct, they would hurl forth huge projectiles without any sound of explosion, and earthquakes would not be accompanied by the low rumblings which add to our terror. Because there is no atmosphere, there are no clouds to temper the torrid heat of an ever-serene sky. Because there is no atmospheric electricity, there are no storms, and no riotous blasts roaring dismally through those forests of monstrous peaks which stand fixed in the immobility of death. There is nothing but the abrupt changes of temperature, with their alternating effects of expansion and contraction, to bring to pass the gradual breaking down of the mountain masses.

This question of the temperatures at the surface of our satellite is still much discussed at the present time, and

¹ Astronomy and Astrophysics, xi, p. 778.

I must admit that it is exceedingly difficult to form an opinion on the subject. The period of rotation, it has been said, is equal to that of revolution. Hence at the instant of new Moon, when our satellite is between us and the Sun, the face that is lighted up is the opposite one to that which we see, and an interval of rather more than fourteen days has to elapse before the conditions are completely reversed. Throughout this interval, the lunar hemisphere which was in darkness when the Moon was new will have been continually directed towards the Earth, but in consequence of the revolution it will at the end of that time be turned to face the Sun also. There will therefore be broad daylight over this part of the Moon's surface, and we shall have "full Moon."

A long day, lasting about a fortnight of our time, and a night of the same length—that is the state of things to which the Moon is subjected. In these circumstances it is clear that from the moment when the Sun sinks below its horizon any region of the Moon's surface must cool very rapidly and its temperature must fall to a value not far removed from absolute zero, say to about -265° C. As to this minimum temperature there is no dispute, and it is only in regard to the maximum that disagreement arises; some scientists, like Lord Rosse¹ and more recently Véry² consider that it may reach, and even exceed, the temperature of boiling water, since there is no atmosphere to absorb part of the heat radiated by the Sun; but others, like Langley,³ maintain with equal probability that, precisely because of this absence of an enveloping atmosphere, the heat which is received is immediately lost by radiation, and the question is still unsettled. Measurements by means of the bolometer, which is a thermo-electric pile of extreme sensitiveness, have not succeeded in putting an end to the discussion; they have clearly demonstrated that the Moon does send us some heat, but

¹ *Proceedings of the Royal Society*, xvii, p. 443.

² *Memoirs of the National Academy of Sciences*, iv, p. 193.

³ *American Journal of Science*, xxxviii, p. 428.

any body whatever which was exposed to the Sun would do as much, and so the uncertainty remains.

Has this absence of any atmosphere—the cause of all these disputes—always been characteristic of the Moon which now rolls lifeless and inert above our heads? To

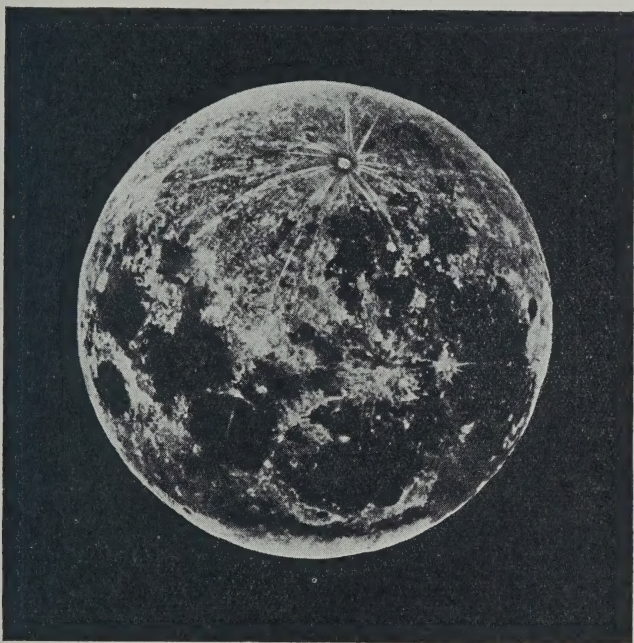


FIG. 26.—PHOTOGRAPH OF THE FULL MOON, SHOWING THE LINES RADIATING FROM TYCHO (THE BRIGHT CIRCUS NEAR THE TOP OF THE FIGURE)

this question we can as yet give no answer ; the arguments on either side are not decisive. No doubt, a high degree of probability may be claimed for the belief that the air and water may have been absorbed by the porous rocks, or have entered into chemical combinations with their elements, but nothing that we see can legitimately entitle

us to suppose that the relief of the Moon's surface was the work of any actions like those which produce erosion on the Earth. On the contrary, recent measurements of the albedo, or whiteness, of different parts of the lunar surface justify the statement that if there were ever any glaciers on the Moon they have now disappeared for ever.

Thus the facts—and by them we mean the results of

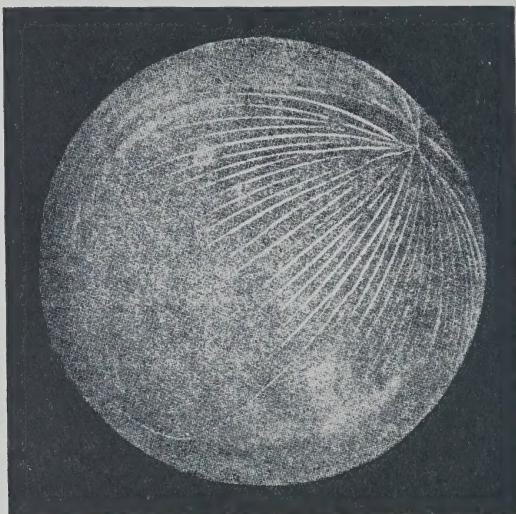


FIG. 27.—CRACKED SPHERE OBTAINED BY NASMYTH BY SUBJECTING THE LIQUID CONTAINED IN A CRYSTAL GLOBE TO A POWERFUL INTERNAL PRESSURE. (THIS SHOULD BE COMPARED WITH FIG. 26)

that experimental method which we ought never to forsake—are gradually tending to produce agreement in regard to the details which have been observed on the Moon's surface. Does this mean that we have no longer any doubt as to the process by which this world has come to present such a different aspect from our own? If we had any illusions on this point, the numerous conflicting

theories which are being put forward at the present time would suffice to remove them. Let us try, however, as we did in the case of the Sun, to sketch in broad outline the manner in which things may possibly have happened.

The most casual glance at the disc of the full Moon, with its diameter magnified some twenty-five times, cannot fail to detect the whitish streaks radiating like spokes of a wheel in long bright lines from such circuses as Tycho, Copernicus or Aristarchus ; as much by reason of their number as of the distance to which they are prolonged, they are in fact the dominating feature, the most noteworthy characteristic, of the lunar surface. Some of them stretch along great-circle arcs to astonishing distances ; one in particular, starting from Tycho in the southern hemisphere, is continued into the northern hemisphere and terminates only after a lengthy journey of nearly 1,600 miles, and there are a great number which reach to more than 50 or 60 miles from their centre. It is strange, too, to find that these radiating lines do not seem to be affected by the irregularities of the surface relief ; they proceed with the same intensity, the same width, the same clear colouring over the summits of the circular mountain walls as they do over their flanks or over the plains within them ; they look indeed just as if they had been painted on the surface, or were formed of some material that had been simply deposited on it.

M. Puiseux tells us that they consist of volcanic cinders, and are the consequence of formidable eruptions which have taken place from particular craters. But why did they take these different directions ? The same astronomer gives us the answer : it is, he says, because the winds changed during the continuance of the eruptions, and caused the smoke and ashes to spread out in lines or streaks in all possible directions.¹

They must, one feels, have been a strange kind of tempests, coming so opportunely to prevent the accumu-

¹ See on this subject P. PUISEUX : *La Terre et la Lune*. Gauthier-Villars, Paris, 1909.

lations of volcanic matter from being concentrated in a single region! And there is another question that one is inclined to ask: Why should these immense radiating lines of cinders have remained the special privilege of so small a number of volcanoes? This question is not answered by M. Puiseux.

Great as is the authority which attaches to the name of a scientist to whom we are indebted for a remarkable series of studies dealing with our satellite, as well as for the

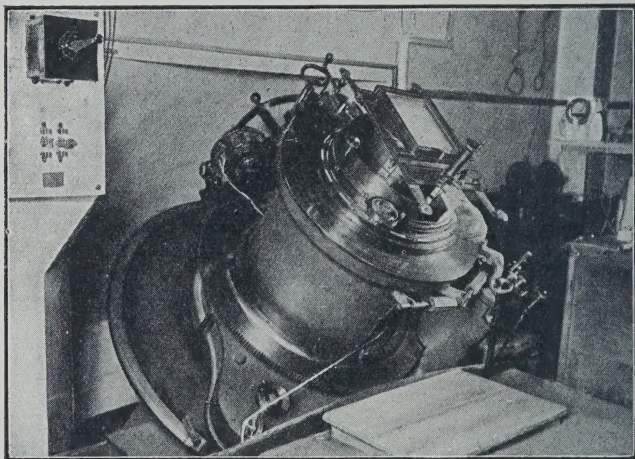


FIG. 28.—EYE-PIECE OF THE COUDÉ (OR ELBOWED) EQUATORIAL AT PARIS OBSERVATORY, WHICH WAS EMPLOYED TO TAKE THE PHOTOGRAPHS FOR THE ATLAS OF THE MOON

colossal task which he undertook in collaboration with MM. Loewy and Le Morvan and which resulted in the enrichment of astronomical science with an unrivalled photographic atlas of the Moon, I must frankly confess that the theory of volcanic ashes being spread out in such long and regular bands by atmospheric causes has never to my mind seemed satisfactory. An observer who looks at the Moon without any preconceived idea is much more

likely to be reminded of systems of cracks radiating from a centre. I believe it was Nasmyth who first succeeded in obtaining similar cracks on a crystal globe, running along great-circle arcs, by means of expansion. In 1890 Daubrée carried out experiments of the same kind, and proved once more that if we wish to attempt an explanation of the great lines of fracture which are observable on

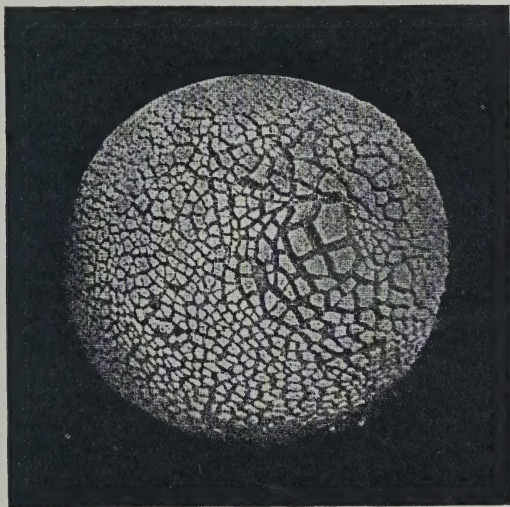


FIG. 29.—SPHERICAL BLADDER COVERED WITH PLASTER, SHOWING THE CRACKS FORMED BY DILATATION

(From experiments by the Abbé Th. MOREUX)

certain planets, we must have recourse to actions the very opposite to those which occur in the case of the Earth. In 1897, I in my turn took up the experiments of Daubrée, entirely altering the method of operation so as to be able to co-ordinate the results; the expansion was effected, not by increasing the internal pressure, but by creating an external vacuum by means of the air-pump. The globes upon which I experimented were covered with plaster, and I gradually obtained on their surfaces a variety

of effects ranging from the kind seen in the case of the Moon to those which have been observed on the planet Mars.¹

It is scarcely likely, however, that the surface of the Moon or of Mars should have suddenly burst, one fine morning, as the result of powerful internal pressures, like

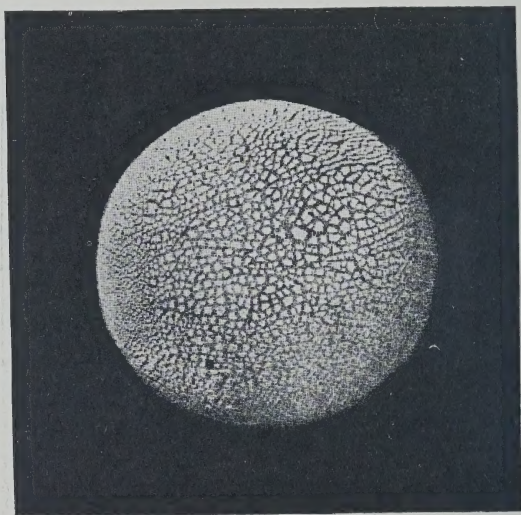


FIG. 30.—THE SAME BLADDER, WITH A THINNER LAYER OF PLASTER ;
THE CRACKS ARE NOW MORE NUMEROUS

a balloon which had been blown up too strongly. The reason for the cracks, though in itself quite simple, is a less obvious one, and we must look for it farther back ; it is to be found in the difference in the way the planets have been formed, about which there is no doubt. In some the process of formation must have been rapid, as in the case of Mercury, Venus and the Earth for which we find that the density has a high value ranging from 5.33 to

¹ See "Revue des Questions scientifiques," Th. MOREUX : *Vues nouvelles sur la planète Mars*, October 1898.

5.52. In others, condensation must have been checked, and the materials agglomerated slowly. Apart from any theory of cosmogony, we know that the proximity of Jupiter in the case of Mars, and of the Earth in that of the Moon, must have proved a serious hindrance to their condensation, and the fact is shown by their low densities, 3.33 for the Moon and 3.93 for Mars.

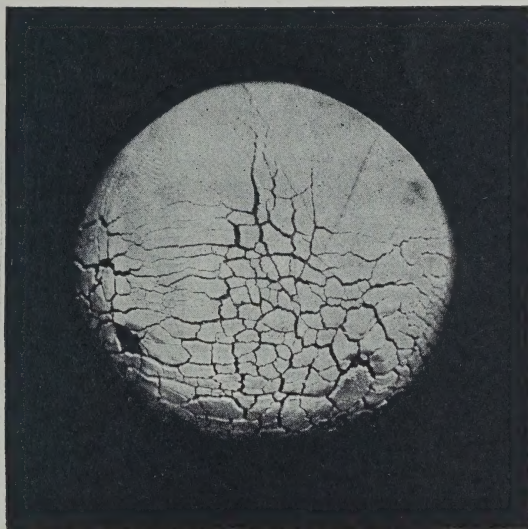


FIG. 31.—THE SAME BLADDER, WITH A DRIER AND THICKER COVERING OF PLASTER

In such conditions as these, the agglomeration of the materials at the surface must have taken place more uniformly, like the loss of heat and the gradual contraction. It follows from this that, instead of being obliged to act at every moment as the covering of a rapidly diminishing central core (which in the case of the Earth explains the crumplings of the surface), the crust of the Moon or of Mars quickly became too small to contain the underlying

spherical mass, and hence arose those cracks which remind us of the appearance of a clay soil when it becomes dry through exposure to the heat of the Sun.

If we now recall the theories which M. Joly put forward in regard to the alternation of geological and incandescent phases, everything is explained. After a thin solid crust had been formed, the viscous mineral stratum underneath

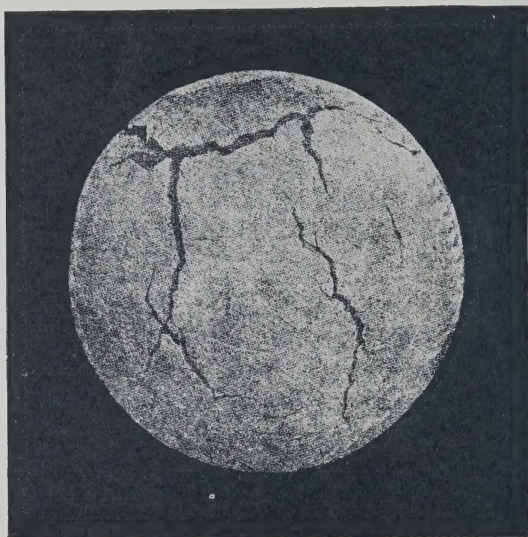


FIG. 32.—GLOBE FORMED OF CLAY WHICH IS BEGINNING TO GET DRY
(From experiments by M. DU LIGONDÈS)

became the seat of fresh activity, and was compelled to force up through the cracks first of all gases produced by its expansion, and then metallic lavas, exactly as in the case of the Earth. Thus these regions very quickly became special centres of volcanic action, and this accounts for the existence of the numerous craters situated along the line of the cracks. More and more cracks were produced during the alternating geological periods of the Moon's

history, though as time passed this occurred to a diminishing extent. So true is this that, as even M. Puiseux admits, they are now a regular feature of the lunar surface ; they were formed in every period, and they occur in every section of the globe ; the most recent ones can still be seen, for in consequence of the increasing thickness of the crust they have not been filled up by the outflow of material from the interior.

It cannot be denied that after a certain stage the process also brought about a severe crumpling of the crust, and internal shrinkage showed itself in the same way as on the Earth. But we must remember in this connexion that the eruptive forces on the Moon were six times more powerful than they are with us, and this leads us to the consideration of another aspect of the phenomenon.

The distinction which we have made between the circuses and the " seas " in our classification is after all a somewhat artificial one, for all the depressions on the Moon's surface are alike bounded by curves whose concavity is inwards ; seas, circuses and ring-mountains have all got at their outer edges great masses which are piled up in a circular or polygonal arrangement, and we pass without noticing it from one kind to another. This is the second characteristic of the Moon's surface relief, and it may be added that in regard to this also the magnitude of the phenomena has decreased with the lapse of time. The result of visual and photographic examination leaves us in no doubt that, speaking generally, the seas were formed before the circuses, of which the areas are less extensive ; and that among the latter those having a very small diameter are later than the larger ones on the walls of which they are often located. These circuses, as we have seen, do not in the least resemble volcanic craters on the Earth, yet they may well be the result of some kind of volcanic activity. Let us consider the method of their formation.

It is clear, from the experiments which I carried out

with elastic globes, that as the cracks increased in number they tended to an arrangement in the form of a polygonal network, with the meshes closely crowded together. Through the wide gaping crevices the lava would be pushed through at some given moment, and this would harden and become unyielding through being suddenly cooled. As more material was forced through from the interior, it would therefore swell out even beneath the cavities, and lead to the formation of domes, of which a few specimens are still found. "We should thus have, as it were, gigantic bubbles, which have burst and so produced enormous depressions of elliptic or circular shape. In this way great depressions like the Mare

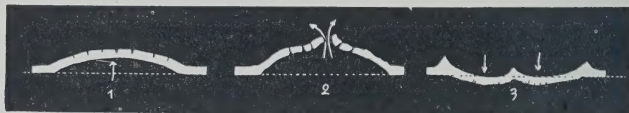


FIG. 33.—FIGURE SHOWING HOW THE INTERNAL GASES LIFTED THE LUNAR CRUST, WHICH AFTERWARDS COLLAPSED TO FORM CIRCUSES WITH A CENTRAL PEAK

Crisium, the Mare Serenitatis, the Mare Imbrium, etc., have originated. All of these, in fact, are bounded by mountain masses, whose steepest faces are always turned towards the depressed region within.

"At a later stage in lunar evolution, when the crust had increased in thickness, the swellings were localised within a more confined area, and the resulting depressions have constituted circuses like Tycho, Ptolemy, Theophilus, etc. The existence of the central mountains is also satisfactorily explained on this theory. For lack of room, certain parts of the collapsing dome were obliged to overlap one another. In some cases the uprush of the lava has more or less filled up the bottom of the arena, and overflowed in metallic streams all along the outer walls,"¹ which, indeed, is exactly what we see.

¹ Th. MOREUX : *Un jour dans la Lune*, p. 70. A. Fayard, Paris, 1910,

Volcanoes, in the proper sense of the word, came much later, but they are in general far too small to be regarded as the cause of those mountain walls which bound most of the large lunar formations.

To sum up, the large circuses are due to a process of excavation, and are the result, as I guessed as long ago as 1898, of actions resembling the explosion of a shell. My friend, the distinguished scientist Colonel du Ligondès, enabled me to witness some explosions of this kind, and we found in almost every case miniature mountains in the centre of the depressions, just as is the case on the Moon.

All these considerations show that mechanical principles are the same in all the different worlds which the universe contains, but the interplay of the forces engaged in modelling the heavenly bodies can occur in very different ways and lead to very dissimilar results. It is therefore of immense importance for us to discover the details of the interaction, and this above all others is the end to which our efforts should be directed.

There remains one last question to be considered on the subject of the Moon's relief. Is our satellite an absolutely dead world, or may it be that under the stress of its internal forces changes are produced from time to time upon its surface?

It is a fact that for a long time past certain observers have noted cases in which it seemed probable that changes were occurring; the small crater Linné, the region around Theaetetus, and other parts have several times seemed to show traces of alteration. Great caution is necessary, however, before any solution of this important problem can be accepted. As I have already remarked several times, our knowledge of the Moon's relief is obtained only by means of the shadows cast by the sunlight; and it is obvious that these shadows are changing every moment. It may be suggested that we might wait for the period of a lunar month, and then seize the instant at which the

shadows are in exactly the same position on the Moon's surface. Doubtless, we might do so ; but that would make of it a long-winded task which we should bequeath unfinished to our successors. Indeed, we know that exactly similar phases do not recur oftener than about every 243 days ; and if, in addition to this, we take account of the changes produced by libration, we are entitled to conclude that the same astronomer probably never sees the Moon twice under quite the same aspect. In these circumstances, there appears to be an *a priori* difficulty in making any pronouncement as to possible changes on the lunar surface.

Further, it is to be noted that we could not in any case establish the fact of any alterations except those occurring over a wide area. This is due to the limitations imposed upon us by our optical instruments. In order that two dark or bright spots on the surface of the Moon may be perceived as distinct, when we are employing an object-glass of 50 centimetres diameter, they must be above a quarter of a mile apart. Even the largest telescope in the world, the famous reflector of Dr. Ritchey erected at Mount Wilson, which has been in use since the year 1918, cannot with its enormous diameter of 100 inches distinguish between two spots if there is less than a hundred yards between them.

Instruments of this class will always be rare, and equally rare the opportunities for using them. It is certain, therefore, that if changes take place on our satellite, they must be large enough to measure something more than half-a-mile before they can be observed under the conditions in which most astronomers carry on their work.

The question which we are considering is evidently a most interesting one, and it presents itself, one might say, periodically to those who are engaged on the difficult task of constructing a map of the Moon. But, as we have seen, the attempts at its solution, however praiseworthy in themselves, must be destined to disappointment until we have discovered means for perfecting our optical instru-

ments or for using photographic methods with large telescopes.

WHAT INFLUENCE HAS THE MOON UPON THE EARTH?

We turn to another problem which is as old as the world and yet is still unsolved—though it is reassuring to add that in every decade some progress is made towards its solution.

The cause of the tides has long been known to men of science. In the Middle Ages we may venture to think that it was already suspected, but no agreement had been reached in the matter, as is proved by the fact that when Kepler first put forward the now accepted explanation, his statement met with little approval, and his contemporaries headed by Galileo regarded him as a dreamer.

Since that time, thanks to the analytical methods based upon Newton's law, a great deal of admirable work has been done which has settled the question. It would be out of place here to give even the barest account of this analysis, but it will not be without interest to remind the reader, without having recourse to any elaborate mathematical reasoning, of the method by which the Moon acts upon the elements of our globe.

In the course of its revolution round the Earth, the Moon has to pass through two positions in which it is in line with the Sun. When it is opposite to the Sun, with the Earth between (or, as astronomers would say more briefly, at the moment of opposition), we have full Moon; but if, on the other hand, the Moon and the Sun are on the same side of us (which occurs at the moment of conjunction), the Moon is new. The first and third quarters of the Moon occur half-way between these positions, when the Sun, the Earth and the Moon occupy the corners of a right-angled triangle.

The mass of the Earth is 81 times as great as that of the Moon. But the Moon is not on that account negligible, and we find that its effects depend exactly on the position which it occupies in the heavens. When it is new, its

attraction is added to that of the Sun ; when it is full, the two bodies pull in opposite directions ; and at the quarters, the Moon tends to accelerate or to retard the speed with which our planet moves in its orbit.

In order to simplify the problem as much as possible, let us exclude the Sun from our consideration, and think of the Moon and the Earth as if they were alone in space. When the Moon passes vertically over a region of the Earth, its attraction is exerted upon all objects spread over that part of the surface, and so by means of that attraction it must relieve them of a part of their weight. In this way a man whose weight is twelve stone loses $\frac{1}{3200}$ of an ounce. The same principle must apply in the case of the water which covers a large part of our globe ; but here we have a level surface, so that if the water loses weight when the Moon is overhead, the column of water measured upwards from the bottom of the sea (which we take to be of uniform depth, for simplicity's sake) must be higher than in some other parts in order that the pressure on the sea floor may remain the same and equilibrium be maintained. This bulging outwards of the ocean's surface is what we call the tide.

We see, then, that bodies on the Earth which face towards the Moon have their weight diminished ; and we now have to add—what seems at first sight paradoxical—that the same thing happens to those which are situated at the diametrically opposite part of the Earth's surface. How is this to be explained ? It is due to the fact that the Earth is attracted towards the Moon with a greater force than they are, because its centre of gravity is nearer. Consequently, the tide always involves a double uplifting of the surface of the ocean at opposite sides of the globe. As to the exact time at which the tide occurs at a particular place, that depends upon a variety of causes which have been successfully investigated ; chief among them is the friction occurring between the molecules of water, in consequence of which the effect of the Moon's action is delayed in some places by as much as 36 hours.

A similar retardation has also been suggested in connexion with the tidal movement which is set up by the combined action of the Moon and the Sun in the fluid interior of our globe, in order to explain the fact that the up-swell which is thus produced under the Earth's crust is liable to a slow oscillation. It is supposed that this oscillation might account for the alteration of the position of the polar axis, which has been referred to above. It is likely, on other accounts, that the meteorological action, which I have already mentioned as producing a slight disturbance of this sort, is not sufficient to account for the whole of it, and we are probably dealing in this case with the resultant of a number of extremely complex phenomena, such as the variation of the calorific intensity of the Sun, the magnetic action of both the Sun and the Moon, meteorological changes which bring about an alteration of the magnetic pressure, the tides of the Earth's crust, and so on. In any case, there is no doubt about one fact which tends to support the idea of these oscillations in the internal fluid mass, and that is that earthquake-periods occur in connexion with sudden changes in the rate of variation of latitude.

It is easy to see that the more we study the Moon, the more extended is its sphere of action found to become. The time is past when astronomers like Arago were prepared to deny on *a priori* grounds the possibility of the Moon's influence upon a large number of terrestrial phenomena.

Until the last few years it was denied that the Moon had any power to cause sensible tidal fluctuations in the atmosphere, and the denial was made under the pretext that such a phenomenon was theoretically impossible. It would seem that the history of science has taught us nothing, and learned men still go on falling into the very same error for which they blame the investigators of the Middle Ages with such severity; instead of beginning with the study of the facts, they are content to argue; instead of carrying out experiments, they philosophise.

But however that may be, we have clearly demonstrated that the Moon acts magnetically upon the Earth, although the mechanism of the action is still undiscovered. Moreover, this action on the part of our satellite is exerted differently at different distances. It is equally impossible, since the recent researches of Fr. Colin,¹ to doubt that there really is such a thing as an atmospheric tide; only the tidal wave which helps to determine the weather in tropical regions is often distorted in higher latitudes by meteorological elements which are in a high degree variable. We are thus being brought by the method of experiment to enter upon a fruitful line of study which, we may be sure, holds more than one surprise in store for us.

Has the time come, then, to revive the ancient belief in the influence of the Moon upon living organisms? It may be so, and despite the repeated assertions of contemporary astronomers, I am by no means unwilling to believe that the Moon does act in such a way. I have just been re-reading Arago, who is often quoted as a witness against old superstitions. I find that this famous astronomer made no attempt to settle the question. He stated that some of the facts alleged by certain writers were lacking in precision, but he concluded that the matter was open to discussion.²

In my book *Un jour dans la Lune* I have shown that this question is not less complicated than that of the influence of our satellite upon the weather. At the same time it appears from all the information available that the Moon's action is really effective in increasing the size of the cell. For example, the activity of cryptogamic vegetation, which is generated in stagnant water, seems to attain its maximum intensity at the time of full Moon.³ This might furnish an explanation of the practice, still kept up by many gardeners, of sowing certain plants during the waxing or waning of the Moon, according to

¹ COLIN : *Influence du Soleil et de la Lune sur le baromètre à Madagascar*, in the "Revue du ciel" for August 1919, p. 672.

² F. ARAGO : *Astronomie populaire*, III, 503. Paris, 1857.

³ Th. MOREUX : *Un jour dans la Lune*, p. 99. A. Fayard, Paris, 1910.

the effects which it is desired to obtain. In our latitudes the phenomenon is sometimes counteracted by the inclement weather, but it would seem, according to a number of observers, to be very clearly noticeable in equatorial regions.

To pass from this to the Moon's influence upon men and animals is only a step. Many facts tend to show that certain nervous affections and even some skin diseases exhibit periodic changes connected with those of the Moon. There is nothing impossible in this, and the dependence might very well be explained if it is remembered that the Moon undoubtedly exercises a magnetic and electrical influence upon our atmosphere. In that case the name "lunatic," which was invented in past days, would not be so devoid of meaning as we often like to believe. The subject is one which deserves the careful investigation of any modern physiologists who are willing to approach it with a full use of all the resources which recent science has put at their disposal.

CHAPTER V

THE PROBLEM OF MARS

MARS is the fourth of the planets considered in the order of their distances from the Sun, and comes next after the Earth. Its mean diameter is 4,200 miles, or a little more than half that of our own globe, and its volume is two-thirteenths of ours. But as its density is only 3.93, while the Earth's is 5.52, it follows that the weight of Mars is not much more than a tenth part of that of the Earth.

Its revolution is accomplished in 1 year and 321 days, in an elliptic orbit whose eccentricity is fairly large ($\frac{1}{10}$); and as the planet's axis is inclined to the plane of its revolution at nearly the same angle as is the case with the Earth, there is the same relation in its two hemispheres between the heat of the summer and the cold of the winter as with us. At the same time it is important to remember that on account of the slowness of the revolution, which takes almost two years, the seasons of Mars are double the length of ours.

To complete the statement of all that is known with mathematical certainty about this interesting planet, it may be added that by reason of its smaller mass the effect of gravity is not more than one-third of what it is on the Earth, that the length of the Martian day is 24 hours 37 minutes and 22.67 seconds, and lastly that the mean distance of Mars from the Sun is 141,508,000 miles.

The most recent investigations in connexion with this little world have been concerned chiefly with its physical constitution. At favourable oppositions, it is less than 40 million miles distant from our telescopes; and with a magnifying power of 540 diameters, Mars appears at such

times as a disc whose breadth is seven times as large as that of the Moon when seen by the unaided eye, and possessing therefore 49 times as great an area, and this partly accounts for the number of details which are revealed to a suitably placed observer. The topography of Mars is, however, much more difficult to fix than are the main lines of the Moon's relief even when seen through a not very powerful telescope. It is frequently stated that the planet has no mountain chains, properly so called. But such a statement is entirely devoid of foundation, and the mere fact that we cannot see such formations does not by any means prove that they do not exist. This will be more evident if we compare the cases of the two globes.

The Moon's surface relief is visible to us only in certain conditions of illumination, which are easily described: it depends entirely upon the height of the Sun above the lunar horizon. As the obliquity of the Sun's rays diminishes, the shadows cast by them tend to disappear, and at last when the Moon is full it seems to us that everything is reduced to one level, and no markings remain visible except those due to the different colours of the surface. Now, when the disc of Mars is revealed to us most plainly, its phase is exactly like that of the Moon's disc three days before the full. If to increase the resemblance we imagine the Moon possessed of an atmosphere dense enough to hide by diffusion the slight irregularities at its limb, we can see that the discussions of astronomers on the subject of lunar relief would be reduced to great uncertainty, however powerful the magnification which they had at their disposal. So in the case of Mars we can do no more than guess at the condition of the surface, with what little aid we can derive from the observed differences of colouring upon the disc. And that, as may well be imagined, is no easy task.

By the first quarter of the nineteenth century, it had come to be generally admitted that there were seasons on

this planet resembling our own, that there were snow-caps at the poles which melted almost completely during the Martian summers, and that there were varieties of colouring due to actual differences of land and water, the parts of a ruddy or yellowish tint being continents, and the dark patches and streaks being oceans or narrow seas. From 1830 to 1877, observers who devoted themselves to the study of the planet's surface—Fr. Secchi, Sir Norman Lockyer, Dawes, Kaiser, Terby and others—did little more than expand these conclusions: the dark patches were considered to be seas, in accordance with the spectroscopic knowledge of the day; the large configurations were found to vary in both colouring and outline, although the general plan remained the same; and, lastly, it was found that the seas were joined by more or less narrow bands, to which was assigned the general name of *rivers*.

But a new era for areography opened with the year 1877, when Schiaparelli took in hand a most careful study of this neighbour of ours. At first the maps which he constructed resembled those of his predecessors, save for the greater amount of detail which his contained; the continents were divided up into numerous islands, and additional "rivers" were noted.¹ But in 1881, he altered his method of representation; the rivers which had been depicted as more or less curved were made narrower and straighter, and became arcs of great circles, some of which stretched without any change of direction for distances of 3,000 miles. These configurations gave to the planet an appearance which seemed to betoken some other cause than a merely natural one, and Schiaparelli called them *canals*. He was not, however, the first to use this name, for it had been employed by Secchi in 1859.²

With its network of dark markings, looking as if they had been ruled on the surface, and arranged like the streets in an American town, Mars became by far the most interest-

¹ SCHIAPARELLI: *Osserv. astr. et fis. s. di rotat e s. top. d. plan. Marte*, Rome, 1878.

² *Mem. d. Osserv. d. Colleg. rom.*, No. 3.

ing of the planets ; and the last account of it which the Italian astronomer published after his observations in 1889, depicted it as the strangest world imaginable. " At certain seasons," he said, " these canals divide into two, or rather it would be more correct to say that they are duplicated." In the place where on one night he had seen a single dark line, on the next he noted the existence of two parallel lines 120 miles apart. He even cited a case of duplicating in which the two components were separated by a gap of 500 miles ! A similar phenomenon was afterwards noted by other observers, and this seemed to do away with any risk of illusion. It is important, however, to record the extraordinary case which occurred during the opposition of 1886, when Perrotin and Thollon at Nice observed certain canals as plainly duplicated, while Schiaparelli, at Milan, insisted that they appeared to him to be single.¹

These results were sufficiently astonishing, but they were nothing in comparison with those which were given by the observations of the American astronomer Lowell who, working at the observatory of Flagstaff at a height of 7,200 feet, undertook a systematic study of the planet with a telescope of 24 inches aperture. According to him, the globe of Mars is literally covered with a system of lines like those of a spider's web : 420 rectilinear canals were noted,² and at certain times their junctions were marked by small round spots, which Lowell considered to be oases. The whole arrangement, in his opinion, was an artificial one ; faced by a scarcity of water, the Martians, who were gifted with a high degree of intelligence, contrived to make use of the melting of the polar snows, and by means of a clever system of irrigation directed to the

¹ On this subject the reader may consult with advantage *La planète Mars d'après les travaux récents* (in " *Revue générale des Sciences*" for Nov. 30, 1906), and *La Climatologie de la planète Mars* (*ib.*, Jan. 30, 1909), both by the Abbé Th. MOREUX.

² " *Bull. Soc. astr. de France*," *passim* (the proceedings for the years 1902 to 1905 should be consulted). An examination of the drawings made by observers in the past shows that something like sixty of these canals had already been noticed and recorded before the year 1877.

different parts of their planet's surface a supply of the precious liquid which was essential for the growth of vegetation, and so on.

Although Lowell's ideas were confirmed by several observers at Flagstaff, they were questioned in other quarters, and a considerable number of astronomers withheld their acceptance of them. No one, after careful study, went so far as to doubt the objectivity of the dark

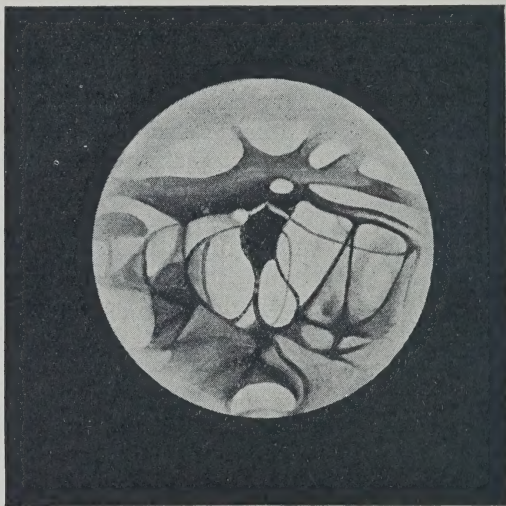


FIG. 34.—PHOTOGRAPH OF THE GLOBE OF MARS, TAKEN BY THE ABBÉ MOREUX DURING ONE OF THE PLANET'S LAST OPPOSITIONS

spots, which changed colour with the seasons ; but this came very far short of admitting the conclusion that the canals were actually the artificial formations which they appeared to be.

In the first place, it is to be noted that later photographs taken by Mr. Lowell himself, and, even more, those taken on a larger scale by Professor Hale, have steadily refused to show the canals arranged in the way that these observers

at Flagstaff saw them. I have myself examined these photographs, and I am able to assert that they look exactly like the drawings which have been made by a good many European and American astronomers, operating with telescopes of larger aperture than the one which Lowell employed.

Some of the canals are large and diffuse, but I have never seen them duplicated ; further, their appearance, like that of the other features of the surface, does not in the least suggest that they are other than natural formations. Mr. Lowell, it seems, must have had some special way of his own in drawing these canals. I ventured upon this remark a long time ago, and since then it has been confirmed by a friend of Lowell's, a teacher of drawing in one of the large American universities. It is frequently the custom over there for the students to be taught to fix the shape of an object by means of straight lines, so that, for example, an arc of a great circle is represented as if it were polygonal in shape. When this is understood, it is not difficult to understand the shapes that have been given to these features of Mars in drawings which were afterwards published as if they represented the actual conditions.

In the second place, observers who have begun by using comparatively small telescopes, and have afterwards looked at the planet through a large instrument at times when the details are most sharply defined, are unanimous in saying that its appearance is thereby completely altered. Such canals as we see through telescopes of small aperture or through instruments constructed with a diaphragm are simply not there any longer. Instead of a dark, narrow and continuous line, we see spots more or less deeply coloured, groups of dark patches along the edge of a brighter region, and ill-defined smudges, which more often than not are discontinuous. These spots are at the limit of visibility in small telescopes, and in observing them the eye joins them together in consequence of its invincible tendency to see such things as one continuous

whole. The duplication of the canals, if it is ever observed, can quite well be explained as due to the fact that, when these objects are of large size, their edges, being in contact with bright spaces, appear darker by contrast.

All these conclusions have been confirmed by the drawings which were made by MM. Millochau¹ and Antoniadi,² using the large equatorial at Meudon—the most powerful telescope in Europe. To quote my friend Antoniadi, who is one of the most skilful observers of the day, “the conclusion is that if, by the canals on Mars, we mean straight lines, then they certainly have no existence; but if, by canals, we mean irregular lines of complex structure which have been produced by natural causes, then their existence is undoubted.”³

Thus the word canal is decidedly ill-chosen, and if we continue to use it we must not allow it to mislead us. The same criticism applies to the name *seas* as a description of the immense dark regions on the surface; they do not contain any water, for in many cases the canals can be seen continued across them, revealed by the difference of their coloration.

It was Lowell, I believe, to whom the first observation of this kind was due; but I confirmed it on several occasions with a moderately powerful telescope at the time of the notable opposition of 1905, when I was able to observe the planet on 98 nights. The following is a quotation from what I wrote at that time on the subject of the seasonal variations: “It is clear that we do not know what the canals and seas of Mars contain; but the hypothesis of a system of Martian vegetation, which rests upon the undoubted fact of seasonal variations, seems to me to be calculated to satisfy all requirements. Mention has been made of the edges of the canals being displaced,

¹ Ch. ANDRÉ: *Les planètes et leur origine*, pp. 66, 67. Gauthier-Villars, Paris, 1909.

² E. M. ANTONIADI: “Bull. de la Soc. belge d'Astr.,” No. 7, 1911. See especially the beautifully coloured drawing of Mars.

³ E. M. ANTONIADI: *L'Aspect physique de la planète Mars*, in the same Bulletin.



FIG. 35.—A DRAWING OF THE PLANET MARS, AS SEEN THROUGH THE
LARGE EQUATORIAL AT THE OBSERVATORY OF MEUDON
(By E. ANTONIADI)

of new lakes being formed, of canals changing their course, etc. ; and all these things can be explained on the supposition that the extent of the floral covering varies from month to month, or from year to year, or even at longer intervals.

“ On the supposition that the planet’s atmosphere is more rarefied than ours—as to which there seems to be no doubt at all—it is plain that the influence of the solar radiation on the soil of Mars is much more pronounced than it is with us. But the radiation, as we know to-day, is itself far from constant ; and this being so, the effects produced by it must also be variable in a high degree.

“ In the case of the Earth, such a statement stands in no need of demonstration ; the distribution of the rain at different periods, the mildness or rigour of the winters, the torrid heat which we get in certain summers, the number of cyclones and storms—all these undoubtedly depend upon the condition of the Sun. And these differences would be all the more accentuated if we had no atmosphere with its abundant water-vapour to regularise the heat which we receive, and distribute it more uniformly.

“ Mars, then, appears to be in a condition which is peculiarly adapted to reflect the variations in the Sun’s activity, and it is not surprising that very extensive alterations in the distribution of the greenish coloured markings on its surface should be observed from year to year. A closer study of our neighbour from this particular point of view would probably be fruitful in results.”¹

These words were written in November, 1906, and I had to wait until 1916 to see them partly confirmed. M. Antoniadi, as we noticed above when discussing the subject of the Earth’s climate, has succeeded in proving that the curve which represents the variations in the melting of the polar calottes of Mars exhibits a striking parallelism with the curve of the solar activity as manifested by the spots. His investigation was carried out for the whole period between 1862 and 1914, and the

¹ TH. MOREUX : “ *Revue générale des Sciences*,” 1906, p. 975.

graph shown on p. 14 will tell more eloquently than any words could do of the correspondence which he established.

If we cannot at present explain every one of the phenomena which we observe on Mars, it is probably because so few data have been collected as yet, and because of the very considerable distance which separates us from the planet. Nevertheless, with my reader's permission, I will try, as I have already done in the cases of the Sun and the Moon, to sketch in broad outline the climatic conditions of this neighbouring world, as my own repeated observations as well as a study of the abundant literature of the subject have presented them to me.

No explanation of the surface variations seems so satisfactory as that which assumes the presence of vegetation in the regions marked by the seas and canals. For example, in 1905 the Syrtis Major, or Sea of the Hour-glass, was of a definitely green colour in summer, and after passing through all the intermediate tints it very plainly took in the autumn the colour of dead leaves. We do not, of course, know what this vegetation is like, and we can only reason by analogy.

What are the conditions essential for life on this neighbouring world? We know that for the living cell two things are indispensable—air and water; are they to be found on Mars or not? This question can be answered without hesitation.

Many phenomena point to the existence of an atmosphere, but at the same time everything leads us to believe that it must be extremely rarefied. Without attempting to assign a figure, even approximately, we may reasonably suppose that the balloons which we send up to explore the upper regions of the Earth's atmosphere, and which rise on the average to a height of twelve or thirteen miles, find themselves floating in a medium of much the same density as the atmosphere of Mars at the level of the surface. In such conditions water could not remain in a liquid state, but would be vaporised even at a low temperature. Now this agrees exactly with what I observed on Mars in 1905.

While Mr. Lowell was claiming that no clouds ever darkened the Martian sky, I was again and again witnessing the formation of haze or mist which was dense enough to hide some of the planet's markings. The objections which Mr. Lowell urged at the time against my conclusions will not stand against a careful examination of the facts, and I should add that several observers have since confirmed what I saw. At the opposition of 1909 I was again able to detect mists which remained for whole weeks above considerable portions of the planet's surface.

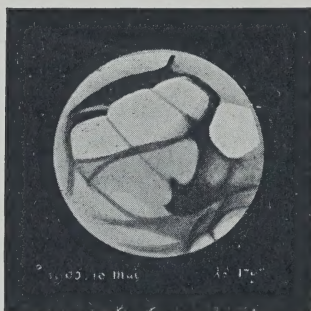


FIG. 36.—THE REGION KNOWN AS THE SEA OF THE SIRENS, OBSERVED WITH A LARGE AMOUNT OF DETAIL

THE SAME REGION TWO DAYS LATER, WITH THE DETAILS BLOTTED OUT OF SIGHT BY A THICK MIST

(From drawings by the Abbé Th. MOREUX)

It is plainly impossible that a sea should be formed in conditions like these, despite the presence of water in the atmosphere. We have still, however, to consider the influence of the temperature. Now, whatever starting-point we take for our calculations, the temperature on a planet at that distance from the Sun must average something like 35 or 40 degrees below zero on the Centigrade scale; and the rarity of the atmosphere of Mars would lower rather than raise this figure. In summer, and at the equator, it may be that the soil gets warmer, and the temperature rises above freezing point, but this does not

alter the fact that the normal climatic conditions on Mars are similar to those at the polar regions of the Earth.

Yet it cannot be denied that the polar snow-caps of Mars are almost completely melted during the summer season, and the canals then show a remarkable development. The spread of vegetation, if it really is such, follows the opposite course to that which we find it taking on our own globe, for it commences near the poles and gradually advances¹ towards the equator, if we are to accept Lowell's observations. It seems, then, as if the established facts are inconsistent with our calculated value of the temperature, and this is what constitutes, in the strict sense, "the problem of Mars." We may state it in this way,—that Mars appears to enjoy a higher temperature than that which its distance from the Sun would seem to justify.

Yet, when the matter is examined more closely, the disagreement has always seemed to me more apparent than real; and all that is needed, in order to get rid of it, is that we should distinguish between the temperature of the air and that of the soil. In his memorable expedition to the North Pole, Nansen remarked differences between the two amounting to as much as 42 degrees! It is to be noted, further, that if the polar calottes are formed not of a thick layer of ice, as on the Earth, but of a thin covering of snow, we can easily imagine that the temperature of the soil of Mars under the influence of the Sun's radiation (which, on account of its rarefaction, the air will do little to absorb), may be high enough to melt the snow at the north and south poles almost completely.

Nor is this all; sufficient account is not always taken of the fact that the Martian seasons last twice as long as ours. The turning of the planet's pole towards the Sun marks the beginning of a long summer; and while the equatorial regions are always subject to the changes of

¹ For further particulars of the most striking cases of this development, the reader may consult Th. MOREUX : *Les autres mondes sont-ils habités ?* chapters vi, vii, and viii, Éditions Scientifica, Paris, 1909.

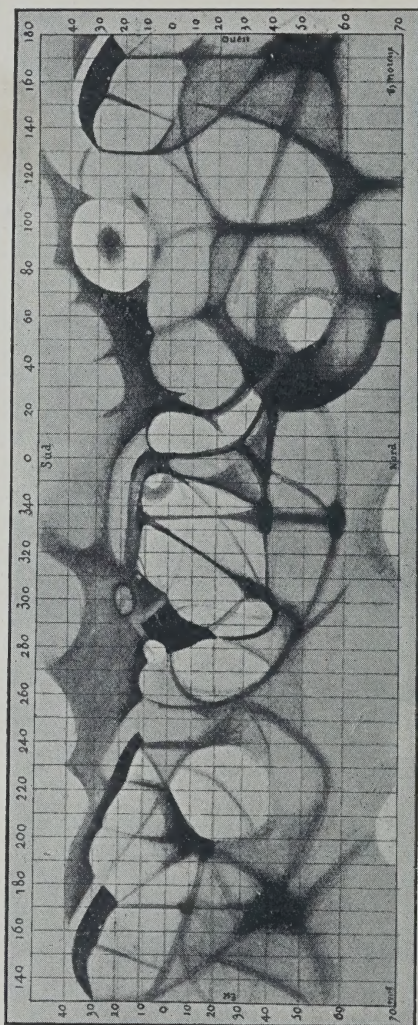


FIG. 37.—PLANISPHERE OF MARS, AS DRAWN BY THE ABBÉ TH. MOREUX AT THE OBSERVATORY OF BOURGES, DURING A RECENT OPPOSITION

temperature resulting from the alternation of day and night, in high latitudes the Sun remains above the horizon for nearly a year of our time. When once the equinox is past, the melting of the snow goes on uninterruptedly. Water-vapour passes into the atmosphere, and it is this vapour which gradually spreads towards the lower latitudes, and produces, even in regions near the equator, the conditions which are favourable to the growth of vegetation.

“It should be noted in passing that the same results would be produced by a chemical change associated with a substance’s hygrometric condition. While, therefore, it is true that in the present state of our knowledge the vegetation-theory appears to explain everything, it ought not for that reason to be regarded as definitely proved. It is a valid hypothesis, but it is not the only possible one.”¹

However that may be, the conclusion seems plain that, assuming the rarefaction of the atmosphere, the Martian climate is of the character which we associate with a polar desert, in which an animal of high organisation could not sustain life; the pressure of the atmosphere is too low for water to remain in a liquid state, and the very plants must be of a rudimentary type,—indeed, they can exist at all only by obtaining their supply of this necessary element from the rare and humid atmosphere which surrounds them, as is done by certain kinds of vegetation on our own globe.

The condition of Mars, then, “seems to be an intermediate one between that of the Earth on the one hand and that of the Moon on the other, and it is probable that the phenomena of which we are the distant spectators are merely the last manifestations of a life which is becoming extinct. Slowly, very slowly, time does its work, and insensibility overtakes the planet as a consequence of the cold which sooner or later puts every world to sleep and gently leads it along the road to death.”²

¹ TH. MOREUX : *op. cit.*, p. 120.

² *Ibid.*, p. 121.

Mars possesses two satellites, which have been discovered in comparatively recent years. They were first observed in August 1877 by Asaph Hall with the large telescope at Washington, having previously escaped the notice of Sir W. Herschel, Lord Rosse, and Lassell, in spite of the powerful instruments with which they were equipped.

The inner satellite, Phobos, revolves round the planet in 7 hrs. 30 mins., in an orbit whose radius is only 5,700 miles. It is the only satellite that is known to revolve in a shorter period than that of the rotation of its primary. A similar state of things exists in the case of Saturn's ring, and it seems impossible to account for it on Laplace's theory; we shall return to the subject when we come to study the details of that remarkable formation in the chapter on Saturn.

If a race of Martians exist, the spectacle which Phobos presents to them must, on account of its rapid motion, be a very curious one. They would see it rise in the west and set in the east, having in the meantime taken about five and a half hours to complete its journey across the heavens.

The other moon of Mars, Deimos, is at the greater distance of 14,000 miles. It takes 1 day 6 hrs. 37 mins. to complete its revolution; and as this is not much longer than the period of the planet's rotation, its eastward orbital movement among the stars only slightly exceeds its diurnal movement towards the west, and consequently an interval of nearly 132 hours elapses between one rising and the next. This interval is longer than four of its "months," so that all the changes of phase occur four times within its duration.

These satellites are very small, and appear to us as between the tenth and twelfth magnitudes. The diameter of Phobos measures, it would seem, about a dozen miles, and that of Deimos only half as much; but these elements are very difficult to fix, for different values are obtained by different methods, and the disagreement amounts in some cases to a doubling of the figures. It is

certain, at any rate, that the satellites of Mars occupy a mean position, as regards mass, between the objects we call meteorites and the larger asteroids. These last will form the subject of our next chapter.

CHAPTER VI

THE MINOR PLANETS, OR ASTEROIDS

WHEN, in the year 1618, Kepler discovered his third law, that the square of a planet's period of revolution was proportional to the cube of its mean distance from the Sun, the plan of the solar system was definitely fixed. In other words, a convenient method of representation of the system was now possible, and it only remained to determine the scale of numbers which would give the values of the different distances. To achieve this result, there was no need to do more than measure the distance of one of the planets from the Sun; and then the careful observation of the periods in which all the rest completed their revolutions would give the size of their orbits. The method was thus based partly on theory, partly on observation; the latter could not be dispensed with unless some law could be discovered to supply the necessary data, and no such law was known. Yet it was impossible to suppose that the distribution of the planets was determined simply by accident.

Suppose that we write down a series of numbers beginning with 0, 3, 6, each being obtained by doubling the preceding one; we shall have:

0, 3, 6, 12, 24, 48, 96, 192, 384,

We then add 4 to each of them, and so obtain:

4, 7, 10, 16, 28, 52, 100, 196, 388.

If finally we divide each number of this last series by 10, we get:

THE MINOR PLANETS, OR ASTEROIDS 117

0.4	0.7	1.0	1.6	2.8	5.2
Mercury	Venus	The Earth	Mars		Jupiter
	10.0	19.6	38.8		
	Saturn	Uranus	Neptune		

The resulting figures written above the names of the different planets represent very closely the distances which separate them from the Sun, the Earth's distance being taken as the unit. The only case in which there is a wide discrepancy is that of Neptune, whose distance is not 38 but 30.

This law, often regarded as merely empirical, has been called Bode's Law by a good many writers, after the name of the man who announced it in 1778. But in point of fact Bode had borrowed it from Titius who had already put it forward in 1772; and even Titius himself had learned it from an earlier astronomer named Wolf (1741).

The probability of Wolf's law being correct was greatly strengthened in 1781 by the discovery of Uranus at a distance from the Sun which agreed with the rule. A glance at the series of figures, however, shows that there is a gap between Mars and Jupiter. At this point there is a vacant place for a planet; and the conviction that this was so led astronomers to search the heavens for the missing object. An association of twenty-four members was formed for that purpose, but for a dozen years their efforts were unproductive of results, and they were already getting discouraged when, on January 1, 1801, a Sicilian astronomer named Piazzi, who was not actually a member of the association, announced the existence of Ceres, just in the right position to fill the gap.

The announcement was misleading. Ceres was certainly a planet, but such a small one that it hardly compensated for the pains taken to discover it. Its diameter, indeed, is no more than 487 miles, and its mass, which has since been calculated, would not be more (on the assumption

that its density is much the same as that of Mars) than $\frac{1}{5800}$ of that of the Earth, while the intensity of gravity at its surface would be $\frac{1}{22}$ of what it is with us.

Nevertheless, this was the beginning of a succession of surprising discoveries. In the following year (1802) Dr. Olbers discovered a companion for Ceres ; this was Pallas, with a diameter of 304 miles. The new-comer followed almost the same path as its predecessor ; and the two bodies, which are like a pair of twins, are just in the position which had been foretold by the experimental law. Olbers thereupon hazarded a theory and a prediction, of which the latter has been abundantly realised : he suggested that there was formerly a large planet there which had one day exploded, and that these two portions which had been found were probably the forerunners of many others to be discovered later. And indeed, in the years which followed, the number of these small planets was increased, as he had foretold. By the year 1845 five of these "asteroids" were known, and ever since that time discoveries have succeeded one another uninterruptedly, so that at the present time as many as a thousand of these little bodies have been observed.

At first the astronomers who were searching for asteroids were content to compare the region of the heavens near the ecliptic with good star maps, and to note any luminous points which were not marked in them, but that was a slow and tedious method of working. Since 1891 photography has been utilised for the purpose ; the telescope is made to move round in agreement with the apparent rotation of the heavens, and thus the stars are photographed on the plate as round and sharply defined points, while if a planet happens to be in the same celestial field its own movement towards the west will cause it to describe on the plate a little trail, longer or shorter according to the time allowed for the exposure, and so it cannot fail to attract the attention of the astronomer.

Quite recently, the contrary method has been suggested as being more effective. A movement is imparted to

the photographic apparatus exactly agreeing with that which must be possessed by the small planet that is being searched for ; the result is that its image will be perfectly round, while the stars will be represented by the trailing lines. This arrangement makes it possible to detect much smaller asteroids, for the good reason that the effect of their light upon the sensitive plate is accumulated during the whole time of the exposure.

By whichever way it is carried out, the search for the minor planets is a long and troublesome task. It is not enough, as might be supposed, to register the points of light, but it is necessary to go on to identify them. And this is no easy matter ; many of the asteroids have diameters which scarcely exceed the dimensions of Paris itself ; all of them, as they revolve in their orbits, are subject to incredible disturbances due to Jupiter ; and their paths cross and re-cross to such an extent that if their trajectories were represented by means of material rings, as d'Arrest ingeniously suggested, it would be possible, by taking hold of any one of them at random, to lift all the rest. To add to the catalogue of the minor planets, therefore, becomes ever more difficult ; and anyone who takes such a task in hand must not be discouraged if he ends, again and again, by establishing after prolonged calculations that the planet suspected to be a new discovery is only an old and well-known member of the list which has been tracked down several times already.

Yet there are many astronomers who have devoted themselves to this search, deceptive as it often is. Palisa at Vienna, Wolf at Heidelberg, Peters at Clinton, Charlois at Nice—the last-named beating all previous records—have each added to the catalogue from 60 to 100 asteroids at least. When we take account of the difficulties arising in connexion not only with the elements which constitute the peculiar characteristics of one of these small bodies, but also with those depending upon its complicated relations with its neighbours, we are less disposed to smile at the action attributed to Professor Watson who, as Miss

Clerke tells us, "made testamentary provision for his twenty-two clients, lest, for lack of computational care, they should relapse into their former outcast condition."¹

We must mention one more peculiarity which increases the complexity of the problem. Instead of being confined to the narrow zodiacal band across the heavens in which we are accustomed to observe the larger planets, the asteroids, by reason of the inclination of the planes of their orbits to the plane of the ecliptic (which for some of them is very considerable), get lost among the constellations of stars far removed from this plane of reference. The mean value of this inclination is about 8 degrees, but this value is exceeded in many cases; there are some fifty of them for which the inclination is greater than 20° , for about twenty it is more than 25° , for six it is more than 30° , and finally we are acquainted with two for which the inclinations are respectively 43° and 48° .

This property is met with again in the comets, and is not the only link of connexion between them and the asteroids. It is proved by Kepler's second law that celestial orbits are bound to be conic sections: they may be circles or ellipses or parabolas or hyperbolas, but the ellipse seems to be the most frequent curve in our solar system. Sometimes the elliptical orbit exhibits a very small eccentricity, as in the case of the ordinary planets; sometimes, on the other hand, it is very much greater, as in that of the comets. Now the asteroidal type of orbit provides a transition from the one extreme to the other, and this will be made clear by the actual figures.

If we take the orbit of Mercury, which is the most elliptical of those of the eight principal planets, we find that its eccentricity has the value 0.205; while, among the comets, the value 0.402, given by the least elliptical of them (Tempel I.) represents a minimum. The interval is a large one, but it is filled up by the values furnished by the minor planets, whose eccentricities range from that

¹*The Concise Knowledge Astronomy*, p. 314. London, Hutchinson and Co., 1912

of Mercury to that of the comet Tempel I. Indeed we know of five asteroids whose orbits have a much greater eccentricity than this, the values being between 0.41 and 0.65, so that these small bodies may in fact be regarded, from this point of view, as periodic comets.

Such considerations have an interest which the careful observer is not likely to overlook; and we cannot help feeling that sooner or later they will have to be taken into account in the investigation of the still unsolved problem of the way in which these fragments of dust, whirling round between Mars and Jupiter, first came into being.

From the time of the earliest discoveries, Olbers claimed to see in this assemblage of tiny worlds the result of the explosion of a single planet. But, if this were so, the laws of celestial mechanics would require the fragments, in spite of the scattering produced by the explosion, to pass in the course of their revolution through the position at which the initial catastrophe occurred. Now nothing of the kind happens; and the intersections of the different orbits vary as much as the mean distances from the Sun, and range over a region 340 millions of miles in breadth, which is in fact the whole wide interval separating Mars from Jupiter. Further than this, the outlying sentinels of this army of asteroids, like Hector, Achilles, Patroclus, Nestor, and two others, encroach in the course of their revolution on the domain reserved for Jupiter and its family of satellites, and their distances in aphelion are greater than Jupiter's; these constitute the *Trojan* group. Meanwhile, within the orbit of Mars there exists another group known as the *Martian*, and comprising Eros, Alinda and Albert, whose distances in perihelion are less than that of Mars.

Although the rate of addition of new discoveries seems to have fallen off in recent years, it is now justifiable to state definitely that the asteroidal ring will be found to pass far beyond the narrow limits in which at present we see it confined. The phenomenon must in fact be generalised; and we are here confronted by a process

which attains its maximum effect between Mars and Jupiter, in the region where, long before Bode, Kepler had placed a planet: "*Intra Martem et Jovem, interposui planetam.*" Room for a planet there certainly was, and we see the materials which might have composed it, but the fact is that these materials were never able to condense and agglomerate so as to give rise to a single body. The formation of such a body was checked from the first, and we must try to understand the reason for this.

The most complete statistics at once reveal the fact that the distribution of the minor planets is by no means uniform. The average value of their mean distances from the Sun, in terms of the Earth's distance as unit, is not 2·8, as Wolf's or Bode's law would have predicted, but 2·65; at the same time, this figure is far from representing the manner of their distribution, for we find numerous regions in which they are crowded together and others which are unoccupied. Now as early as 1866 it was shown by Kirkwood¹ that these gaps were to be found more particularly at such distances that if there had been any masses revolving there, the periods of their revolution would have been exactly commensurable with that of Jupiter, by such simple ratios as, for example, $\frac{1}{2}$, $\frac{2}{5}$, $\frac{3}{5}$, and $\frac{2}{3}$. Thus the asteroids are known to be scarce exactly in those regions where one of them might have revolved, say, five times while Jupiter revolved twice. This "law of commensurability" clearly does not hold good in every individual case; the action of the large planet is exerted upon all the members of the asteroidal system, tending to collect them in the neighbourhood of its own orbital plane and to draw out their orbits towards itself, so that it may happen sometimes that a mass is pushed out from a given group and thrust into one of the gaps. But that we are here witnessing one of the effects of planetary attraction is definitely proved by the fact that the curve of distribution of the minor planets, with its regions of congestion and emptiness, resembles in its details the variations in

¹ See SMITHS, *Rep.*, 1876, p. 358, and 1888, p. 42.

the thickness of Saturn's ring, which also is formed of cosmical dust subjected to the attractive influence of the central body.

The comparison, of course, must not be pressed too closely. From the point of view of their masses and constitution, bodies possessing a diameter of 10 or 50 miles are quite unlike the particles of which the ring of Saturn is composed. However, the total mass of all the asteroids is still a matter for investigation. Le Verrier had calculated that it could not exceed an upper limit equal to a quarter of the mass of the Earth, but other considerations made it clear later that this upper limit had been put much too high, and that the total mass must be less than that of the Moon.¹

Again, in regard to the problem of their constitution, all that can be said is that the brightness of the individual asteroids differs enormously, and consequently certain astronomers have been led to think that some of them may possess an atmosphere; but if we accept the kinetic theory of gases, and the results which Johnstone Stoney deduced from the theory in regard to the critical velocity of the molecules at the surface of a planet,² we are entitled to ask by what miracle an asteroid could contrive to retain any of the small atmospheric particles on its surface. It must be remembered that even on Ceres, the largest asteroid that is known, a stone projected with a velocity of 1870 feet per second would never fall back again; in the case of a planet whose diameter is only 10 miles, this critical velocity is reduced to 36 feet per second; and the movements of the molecules of a gas are far more rapid than these. Lastly, a fact has been observed which is, if possible, still more remarkable,—namely, that most of the asteroids which can be observed with our optical instruments exhibit fluctuations in their brightness which cannot be adequately explained by the supposition—probable

¹ *Contes Rendus*, xxxvii, p. 797; *John Hopkins Un. Circ.*, January 1895; *Observatory*, xviii, p. 127.

² *Astrophysical Journal*, vol. vii, p. 25. See also the volume in this series entitled *Où en est la Météorologie*, by A. Berget, chap. I.

enough in itself—that their phases change in accordance with their positions.

Here, then, in this limitless field which is revealed to us by recent observations, we may safely assert that the problems which still await solution far exceed in complexity those which were solved or even recognised by our predecessors.

CHAPTER VII

JUPITER

IT would seem at first sight as if the girdle of asteroids had been originally intended to mark the extreme limit of the solar system. We have hitherto been considering the materials distributed between the Sun and Jupiter, out of which planets were formed ; and the largest part of these materials is to be found near the middle of the interval, and constitutes the planets Venus and the Earth. These two bodies, which are of nearly the same size, are flanked on the outer and inner sides by the two little planets Mercury and Mars ; and circling round all four are the thousand or so of asteroids, indicating the greater rarefaction of the nebular mass originally surrounding the Sun. A little farther off, one would think, the void ought to be complete.

But actually it is not so. In this farther region we find another distribution strangely resembling that of the asteroids, and after the relatively empty space inhabited by them the density of the original nebula is once more strongly in evidence. A series of monster planets commences with Jupiter and extends as far as Neptune. In discussing them we shall enter a region altogether unlike the one that we are leaving behind. On the one side, we have had comparatively small planets like the Earth ; on the other, we have bodies of enormous size. Again, the former had a high density, represented on the average by the figure 5 ; the latter are of low density averaging 1.26, and in this respect offer a closer resemblance to the Sun.

Jupiter commences the series, with its huge bulk 1,341 times greater than that of our little terrestrial globe ;

but as its density is only 1.30, its mass is not so great in comparison, and 317 bodies like the Earth would exactly balance it.

Situated at a mean distance of 483 millions of miles from the Sun, this beautiful planet takes nearly twelve years to complete its majestic revolution. Its distance from the central luminary varies by nearly 60 million miles at different positions on account of the eccentricity of its orbit, which is four times as great as that of the ellipse described by the Earth. In spite of its being so far away, Jupiter appears to us at favourable oppositions in the form of a disc measuring not less than 50" in diameter; this is twice as large as the disc of Mars when seen under the best conditions. At such times it is, next to Venus, the most beautiful object in the heavens, and is four times as bright as Sirius, the brightest of the stars.

The observer who looks at Jupiter through even a low-power telescope cannot fail to be struck by its ellipsoidal shape; indeed, between the lengths of the polar and the equatorial axes the difference is as much as 5,600 miles. Such a flattening as this, amounting to about one-sixteenth, indicates rapid rotation; this is another characteristic of the big planets, and bears witness to their fluid state.¹

There is nothing on the visible surface of Jupiter to suggest the existence of any solid continent. From pole to pole the immense globe is swathed in parallel belts of cloud, with their tints infinitely varied and ranging from almost pure white through the whole series of olive-green, reds and browns to the darkest colours. As many as thirty of these coloured bands have been counted at certain times, but as a rule they are reduced to a few, showing white and dark alternately. Three of them, which are the most remarkable of all, are always visible, even in small telescopes, and consist of a bright band over the equator, flanked by two dark ones covering the tropics.

¹ Full numerical details of the planets and their satellites will be found in the author's textbook *Cosmographie*. Gigord, Paris, 1915.

With sufficient magnifying power, the belts reveal a multitude of interesting details which break up their homogeneity ; the most common of these are flaky masses showing like patches upon their edges, with different coloration, and by their means it has been found possible to fix the period of the planet's rotation.

In some respects the appearance of Jupiter reminds us of that of the Sun, and there is one point of resemblance between the two bodies which merits special attention. Carrington, it will be remembered, had proved in relation to the Sun's surface that famous law of rotation, according to which the rotational period is dependent upon the latitude ; and observations of Jupiter have disclosed that the rotation of its surface exhibits a similar phenomenon. The spots at the equator rotate more quickly than those closer to the poles, and have a period of nearly 9 hours 52 minutes on the average. At the same time the curve of velocities does not seem to be so continuous as in the case of the Sun ; it shows sudden irregularities, and these appear to be due to the fact that the bright cloud belts are at a higher level than the dark ones. An exchange of materials goes on constantly by a vertical circulation between the upper and lower layers, both of which consist of gases at a high temperature ; the internal masses are thrust forth to the outermost boundary, and so reach a region where there is a relatively higher velocity, with the result that they are finally driven back in the form of streamers to a region behind the point from which they were erupted, and constitute a lateral drift.

It is possible, too, that the ejected particles have a tendency, as in the case of the Sun, to concentrate towards the equator, after having formed round the planet a sort of corona whose materials gradually fall back again and so accelerate the rotation of this region.

The successive levels, the existence of which in the Jovian atmosphere has often been proved by the doubling or lengthening of the shadows of the satellites, leave no doubt as to the slight consistency of the gaseous layer which sur-

rounds the planet. There are, however, certain phenomena which raise curious points of difficulty here.

The idea that a surface formed entirely of clouds would be unstable has seemed on more than one occasion to be at fault. Certain of the spots exhibit a persistence which from this point of view is disquieting, and the effects which accompany them deserve the most careful attention that we can bestow.

The finest example is offered by the remarkable feature which has received the name of the Great Red Spot, and astronomers are still discussing whether this was what Cassini perceived more than two centuries ago. An object answering to his description was noted by Maraldi in 1708, and then by Gledhill in 1870; but observations that are certainly known to have reference to it date only from 1878. At that time it was oval in shape and of a deep red colour, and its position was nearly in the same latitude as the bright spot which was observed eight years later; but instead of disappearing after two or three years as that one did, it persisted during subsequent oppositions. From the year 1881 it began to grow less distinct, became paler and lost its beautiful red colour, and finally disappeared; yet the cavity which it had carved out in the great southern equatorial belt still remained. At the present time it is visible once more, but it has not entirely regained its former colour. However it is still a splendid object, 30,000 miles long, and is easily seen through telescopes of moderate power.

What is the nature of this extraordinary phenomenon? If it were a condensation of cloud material, it would not be so persistent; and the possibility of its being an island solidly attached to the planet is ruled out by the fact that it floats at the mercy of the atmospheric currents, as has frequently been proved. At the beginning, during the first six or seven years in which it was visible, the period of its rotation was lengthened by six seconds; it then diminished rapidly until 1905, and has remained stationary in recent years; and it is a curious fact that the periods

of quiescence are always periods of lighter coloration, as if the materials which come to it by eruption from the interior bring with them a slower linear velocity, and so produce in it the retardation which is observed.

In 1891, it seemed as if the mystery was going to be

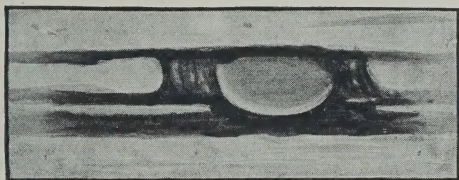


FIG. 38.—THE RED SPOT ON JUNE 20, 1904, EMBEDDED IN THE SOUTH TROPICAL BELT

solved at last. A dark spot was moving towards the immense formation: would it pass above the Red Spot or below it? In either case we should have data to determine its relative level. Occultation or transit—that seemed to

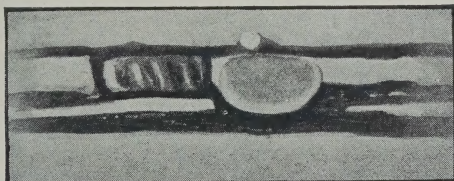


FIG. 39.—BY THE END OF AUGUST, THIS BELT HAD MOVED TO THE LEFT, AND THE RED SPOT APPEARED SEPARATE ONCE MORE
(After STANLEY WILLIAMS)

be the only alternative. But unfortunately the dark spot took another course: it passed by the side of the obstacle, and incurred such damage through being mixed up with it that when at last it got clear it was unrecognisable.

All this, unfortunately, points to no definite conclusion,

and we cannot say more than this : the temperature of Jupiter must be very high, even in the outermost layers, and much more so in those which are beneath. But the intensity of gravity at the equator is more than $2\frac{1}{2}$ times the value to which we are accustomed, and consequently the pressure must very quickly attain a high value as we descend into the gaseous mass. At a short distance below the layer of clouds on the surface, the pressure is not always great enough to counterbalance the effect of the thermal energy, and so there are vertical upward currents, produced by internal explosions ; but lower down these effects are balanced by the pressure, and it may well be that there the materials are in a kind of viscous state and possess great rigidity. These semi-fluid portions may therefore be relatively stable, forming islands as it were in the midst of the more mobile mass. If this supposition is correct, we have the beginnings of an explanation of those phenomena on Jupiter which correspond with those that occurred at that early stage in the formation of the Earth, when the cold of space had not brought about the hardening of its thin habitable crust.

In any case, it would be absurd to ask, as some astronomers have done, what forms of life are possible on Jupiter's surface. It would be at least as sensible to inquire what organisms could adapt themselves to the temperature of our own lime-kilns.

Inasmuch as the huge planet rotates round an axis which is very nearly perpendicular to the plane of its orbit, it has been asserted that no alternation of seasons would be experienced, and some people have talked of Jupiter having "perpetual spring." We have just seen that at the present time the question does not really arise ; but will such conditions be realised in the future, when the globe of Jupiter has cooled ? It cannot be thought so for a moment ; for, even supposing that the Sun is not extinguished by that time, Stefan's law indicates that at the present moment the solar radiations could not produce on Jupiter a higher temperature than 140° Centigrade

below zero. Clearly that disposes of the question, and we need not waste time in discussing Jupiter's climate.

In the days of Galileo, before the invention of telescopes, the solar system came to an end with Saturn ; nevertheless there were reckoned to be seven planets, for the Moon was

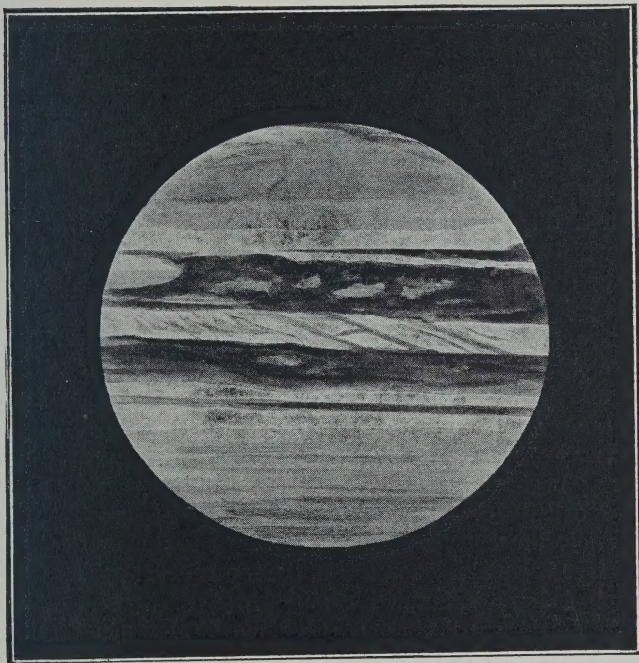


FIG. 40.—THE PLANET JUPITER, WITH ITS CLOUD BELTS. THE END OF THE RED SPOT CAN BE SEEN HIGH UP ON THE LEFT
(From a drawing by the Abbé Th. MOREUX, at the Observatory of Bourges)

counted among the "wandering stars." It was of course well known that the Moon was merely a satellite of our globe, but as no other bodies of that kind were known it was included with the rest so as to make up the sacred

number seven, which seemed to have played an important part in the history of mankind.

Suddenly the news was spread that a spectacle-maker of Middelburg, named Hans Lippershey, had just invented an instrument for making distant objects seem nearer. Simon Marius and Galileo heard about the invention, and each of them succeeded separately in constructing the new apparatus. The two men must have discovered the moons of Jupiter at the very same time ; on January 7, 1610, Galileo observed three little stars close to the great planet, and on the next day, January 8, Simon Marius saw four, of which the second had been missed on the previous night.

This created a revolution in the Universities. Could such a discovery be admitted, when Aristotle had not breathed a word about it ? Clavius, a notable astronomer of the day, went about saying that these luminous points were due to the employment of the telescope. Other men of science, relying upon their doctrine of final causes, asserted that the satellites could not possibly exist, because it was hard to see of what use they could be. Facts, of course, must always be sacrificed to theories !

The new-comers were given names borrowed from mythology ; beginning with the one nearest to Jupiter, they were called Io, Europa, Ganymede, and Callisto. In practice, however, we refer to them by the numbers I, II, III, IV. Taking account of the most recent calculations which I have examined, their distances from Jupiter range fairly regularly from 263,300 to 1,175,400 miles. In regard to size, they differ very widely. Io is slightly larger than our Moon, Europa is slightly smaller ; Ganymede is intermediate between Mercury and Mars, and is the largest of the four ; while Callisto is nearly equal to Mercury. Like our Moon, they revolve in the direct sense, which is also the sense of Jupiter's rotation, and their periods range roughly from 2 to 17 days. Finally, it is to be noted that from the exact calculation of their masses the curious result is deduced that, judging by their den-

sities, they are not solid bodies but liquid or gaseous. It is just possible, however, that in the case of Europa and Ganymede there may be a thin crust on the surface.

The extent of Jupiter's empire remained unchanged for two centuries, but since the opening of the last decade of the nineteenth century a number of new discoveries have been recorded by astronomers.

On September 9, 1892, Mr. Barnard was studying Jupiter with the large telescope at the Lick Observatory, which has an aperture of three feet, and as the light of the planet produced too great an illumination of the field of vision he carefully intercepted it, whereupon he noticed a feeble luminous point nearer than the first satellite. At first he thought it was a small star, but as the days passed all such doubts were removed, and it became clear that here was indeed a fifth moon, situated at no greater distance than 113,475 miles from Jupiter's enormous globe. This new member of the system has not yet been given a name, and it is simply called V, although it is really the first in order from the primary. It revolves very rapidly with a velocity of $16\frac{1}{2}$ miles per second, and completes its revolution in a little less than twelve hours. Few observers are powerfully enough equipped to perceive this tiny world, whose diameter is only some 90 miles.

Fortunately the method of photography is available to supply the deficiencies of our visual instruments; and it was thanks to that method that Dr. Perrine, also of the Lick Observatory, was able to announce to the scientific world that on December 3, 1904, he had discovered a sixth satellite, and then a seventh on January 2, 1905. The two new arrivals might almost be called a pair of twins, since the distance which separated them was relatively very small, and their periods of revolution, which were both about eight months, differed by no more than 14 days.

On January 27, 1908, Mr. Melotte, of Greenwich Observatory, made a further addition to the Jovian system by the discovery of an eighth satellite, slowly revolving

at twice the distance of the seventh in a period of more than two terrestrial years.

In order that we may fully understand the interest of the last discovery, we must return for a time to the subject of cosmogony. Everyone knows the famous theory of Laplace. Struck by the fact that in the solar system all the movements, whether of rotation or revolution, of the planets and their satellites were accomplished in the direct sense, the great geometer in his *Introduction à la théorie des Probabilités* had calculated that the chances were more than four billion to one against this being merely accidental, and had somewhat hastily concluded that the law was general, and that its satisfactory explanation was on the lines of his hypothesis. Now at the same time astronomers were studying the satellites of Uranus, and they proved that their movements were performed like that of their primary, which was in the retrograde sense. The same remark applied also to the satellite of Neptune, discovered by Lassell in 1846.

On the basis of these facts, Faye corrected the theory of Laplace, or rather suggested a new one ; and in imitation of his predecessor he did not hesitate in 1884 to make a prophecy on similar lines. If any new satellite, he said, should ever be discovered revolving round a planet, we might be sure that its revolution would be in the same sense as the rotation of its primary.¹

Less than fifteen years after these unfortunate statements of Faye's, the reputation of his theory had already been destroyed. In 1898, Pickering discovered a ninth satellite of Saturn, which moved in the opposite sense to all the others as well as to the rotation of the planet itself ; and now, in 1908, the eighth satellite of Jupiter discovered by Melotte, exhibited the same characteristic.

In the face of so disconcerting a phenomenon, which seemed to make sport of the theorists, an explanation of some kind had to be attempted, and recourse was had

¹ See H. FAYE : *Sur l'Origine du monde*, p. 192 (1884 edition). Gauthier-Villars, Paris.

to the capture-hypothesis which was already held in high honour in the astronomical world in connexion with those comets which possessed a retrograde movement. The idea was that a body wandering by chance in the heavens had been caught in the toils of Jupiter or Saturn, which had snapped it up as it passed, and kept it prisoner in the bonds of its powerful attraction. But in that case why are these captured bodies the last to be discovered? Why does not this particular way of revolving occur in the case of the inner satellites? There is the puzzle!

This capture-theory is no doubt possible in itself, but it has always seemed to be like the *Deus ex machina* who is called in to help when all other means have failed; and this criticism will appear all the more reasonable as such cases become more and more frequent. Another example has recently been furnished us by the Jovian system. Beyond the retrograding eighth satellite of Jupiter, Mr. Nicholson, of the Lick Observatory, discovered photographically on July 21, 1914, a ninth satellite, which increased the radius of Jupiter's domain to nearly 20 millions of miles, and this one also retrograded! Another case of capture, shall we say? Rather, let us admit frankly that our present systems of cosmogony need to be seriously revised. It is here, and here only, that the whole of the interest attaching to the discovery of these satellites lies. Their importance consists in the fact that, by refusing to fit into them, they prove the theories of some of our most famous scientists to be worn out.

Yet this last remark must not stand unqualified, and no one should suppose that the observation of the satellites is never of more than theoretical interest. These little bodies have occasionally rendered signal services to Astronomy; by means of their revolution, which takes place in accordance with Kepler's laws, we have a fairly easy method for determining the mass of their planet; even their perturbations are, in the circumstances, of great use to us. And it is interesting to note that, in the solar system, the planets about whose masses there is the greatest

uncertainty are always the ones which are not provided with satellites.

Before the discovery of wireless telegraphy, the phenomena associated with the satellites of Jupiter—their eclipses and occultations—were used even for the approximate determination of longitude by ships at sea. Scarcely a day passes, in fact, when Jupiter is above the horizon, without the four early-discovered satellites either disappearing or re-appearing in their movements round its globe. This is due, in the first place, to the fact that they revolve in a plane which is very nearly coincident with the planet's equatorial plane; and this equatorial plane is, as we have said, but slightly inclined to the plane of Jupiter's orbit, which again is itself almost identical with the plane of the ecliptic. In the second place, it is due to the fact that the periods of revolution of these satellites are all short, so that eclipses, occultations, immersions and emersions, and the passing of their shadows over the planet's disc are all of great frequency. Unfortunately, the Jovian atmosphere is of very considerable thickness, and consequently these different phenomena have not that instantaneous character which is needed for an accurate determination of the time; but such books as the *Nautical Almanack* or *La Connaissance des Temps* still continue to give them three years in advance, in order that they may be available for the use of seamen when the time arrives.¹

It was these phenomena which first enabled us to gain an accurate idea of the velocity of light, and the method which was used deserves to be described here, for it was not only one of great ingenuity but also of very real interest. The following brief account is therefore given.

Consider the time when Jupiter and the Earth are on the same side of the Sun and in line with it. The distance between them is then a minimum, and if we observe the interval which separates two consecutive disappearances

¹ For some years past, *La Connaissance des Temps* has given up predicting the times of the phenomena of Jupiter's satellites to the nearest second, and this is a distinct improvement.

of a satellite behind the primary we shall see that this interval will be repeated before a third occultation. But as the Earth, moving more quickly than Jupiter in its revolution, departs from its first position, the distance between the two planets is increasing and we find that the intervals between the occultations are lengthened. This fact was known to the early astronomers, and, as we

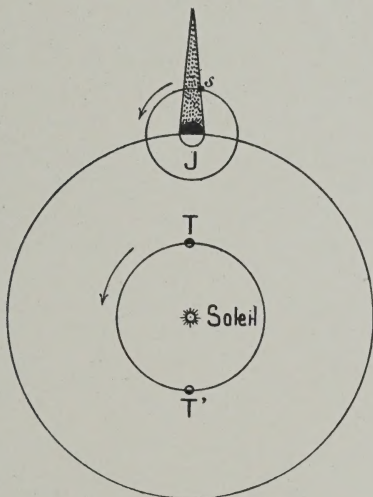


FIG. 41.—MEASUREMENT OF THE VELOCITY OF LIGHT BY MEANS OF JUPITER'S SATELLITES. IN THE FIGURE J REPRESENTS JUPITER, S THE SATELLITE, AND T, T' TWO OPPOSITE POSITIONS OF THE EARTH

shall see, it will give us the velocity of light. Römer, in fact, had noted in 1675 that as between two diametrically opposite positions of the Earth in its orbit these accumulated increments amounted to a total of 16 minutes 36 seconds,¹ and explained the discrepancy between the

¹ This figure would correspond rather with modern observations than with those of Römer, who had reckoned the difference as 22 minutes; but the principle of his deduction was entirely correct, though it was not admitted by astronomers till fifty years later, at the time of Bradley's discovery of aberration.

observed and the predicted times of the phenomena. He had therefore concluded rightly that this represented precisely the time which was taken by light to cross the diameter of the Earth's orbit, which is, of course, twice our distance from the Sun.

When this last is known, the velocity of light is deduced at once. In Römer's time the mean radius of the Earth's orbit was not known accurately, and the result obtained was therefore only approximate—about 190,000 miles a second instead of 186,325. But the method, which is exceedingly elegant, is susceptible of great precision. Actually the time taken by light to reach us from the Sun is 8 mins. 18 secs., and this is called the *equation of light*.

CHAPTER VIII

SATURN

THE appearance of Saturn when viewed through a good telescope is strange and wonderful. Surrounded by a large ring whose golden lustre offers a strong contrast with the duller colouring of the flattened globe itself, it is an object which everybody ought to see at least once in his lifetime. Nowhere in the depths of celestial space, however thoroughly explored, has anything been found to match this magnificent spectacle.

Placed by the early astronomers at the outer limit of the solar system, Saturn accomplishes its long revolution in a period of nearly 30 years, at a mean distance of about 900 millions of miles from the Sun ; but owing to the eccentricity of its orbit there is a difference between its distances at perihelion and aphelion of 100 million miles. We can see, therefore, that in whatever position it may be, its distance from us is always enormous, and this constitutes a real difficulty in the way of its observation. Though our optical instruments have now been brought to a state bordering on perfection, and a great improvement has been made in our equipment by the introduction of spectroscopic methods, our acquaintance with the planet has been but slightly advanced since the days of William Herschel. It is well known that in 1794 this astronomer had concluded from a study of transient spots on its surface that Saturn rotated in a period of 10 hours 16 minutes, but there is the same kind of uncertainty attaching to this figure as we have found in the case of Jupiter ; for the cloud belts which are arranged along the parallels have velocities which differ with their latitude. A spot situated to the north of the tropical belt gave 10 hours

14 minutes 24 seconds, according to observations by Hall of the Washington Observatory ; and more recently, in 1891, Stanley Williams, by using a long series of drawings, arrived at a result which agreed with this within two seconds.

This illustrates the resemblance which we have already noted to exist between the great planets, and in both of them also the very rapid rotation produces as a consequence a pronounced flattening of their globes ; in the case of Jupiter the ratio expressing this flattening is $\frac{1}{16}$, and in that of Saturn it has the yet larger value of $\frac{1}{9.5}$. Both are still in the first stages of their formation, and consist entirely of gaseous matter, but Saturn seems to be the less advanced of the two, as is clearly proved by its low density—lower than that of water. Its physical aspect points to the same conclusion ; its albedo has a higher value than Jupiter's, and the contrasts on its surface do not appear so sharply defined. We can just detect several belts in the tropical regions of a dark grey colour inclined to green, and these melt into a darker tint in which the green predominates as they approach the poles ; the whole is divided by a bright yellow girdle at the equator, in which a number of ill-defined whitish spots are seen rotating. When I look at the disc of Saturn, even at times of clear definition, I am reminded of a painting on which time and dirt have done their work, so that the colours have lost their freshness and the outlines are no longer sharply drawn.

Owing to its great distance from us the planet appears small, but in reality it is a vast globe, 812 times larger than the Earth. The slight differences of aspect between it and Jupiter can easily be explained by the fact that Saturn is relatively the younger body ; in their more fundamental characteristics they are alike, with the same whirling eddies at the surface, the same violent eruptions sending up materials at high temperature from the interior to the outer layers, and the same mode of formation with all that that involves.

If the disc of this beautiful planet has at times proved discouraging to students on account of the difficulties of its observation, the same cannot be said about its rings. The investigation of these has always fascinated astronomers, and has given rise to speculations of the first importance.

It is to be noted, first of all, that the rings lie in the planet's equatorial plane, which is inclined to the ecliptic at an angle of 28° . It follows, therefore, that since the plane of the rings moves parallel to itself, there are two occasions in the course of every revolution on which that plane passes through the Earth, so that we see the rings edgewise; and on the other hand there are two occasions when we see them spread out most widely, projecting beyond the disc to both the north and the south, and so placed very favourably for our observation.¹ The latter position occurred in 1914; then in 1921 the rings were seen in profile, and they will be so again about 15 years later (1934-35), and so on afterwards.

When viewed through a small telescope, Saturn seems to be surrounded by a single ring, and it was thus that the earliest observers saw it in the time of Huygens. But in a powerful instrument the simple uniformity disappears, and three rings can always be distinguished: an outer one, called A, a middle one B, and an inner one C. Each of them has its own characteristics,—one might almost say its own history.

The ring B is by far the most plainly seen. It is of a gold colour, and at its outside circumference there is a brilliant band of high condensation, which makes a splendid contrast with the black line dividing it from the outer ring A. This black circle is nearly 2,000 miles in breadth, and is called after Cassini who noted it in 1675. It represents an actual gap, through which it is sometimes possible to see the planet's disc or even the satellites or a star.

¹ During the critical year in which the ring is presented to us edgewise, it disappears at two (and often three) different times, separated by a short interval. This depends partly on the illumination which it receives from the Sun, and partly on our position relatively to its plane.

Beyond it is the outermost ring A, of a silvery colour which looks more dull and grey in tone than that of B. This ring also seems to be divided by a thin line, which was first noticed by Encke ; but in this case the line is only one-third of the width of Cassini's division, and is by no means well defined, indeed it would seem to represent nothing more than a diminution of the ring's thickness.

In 1850 Bond announced the existence of the third ring C, inside the other two. In order to detect it, one needs to have had considerable experience as an astronomical observer, and an object-glass of more than 4 inches is indispensable. Its inner boundary is at a distance of only 7,230 miles from the equatorial surface of Saturn, and is clearly visible by contrast with the emptiness of space. Its appearance as a whole is of a milky transparency, and the disc of the planet can be quite plainly seen through it.

The size of each separate ring is shown in the following table. The figures given are those which I have obtained from an exhaustive examination of a large number of recent observations, and they may be regarded as extremely close approximations to the actual values :

Width of outer ring A	..	11,690 miles
„ Cassini's division		1,700 „
„ middle ring B	..	17,380 „
„ dark ring C	..	11,320 „

Thus all the rings together, including Cassini's division, constitute a circular girdle around Saturn having a breadth of 42,090 miles, and with its external circumference at a mean distance of 87,600 miles from the centre of the globe.

In comparison with their breadth, it might be said with an appearance of truth that the rings are "without a third dimension." The fact that they disappear from sight in most telescopes at the times when they are presented to us edgewise is in itself an indication that their thickness is very slight ; but it is not entirely negligible,

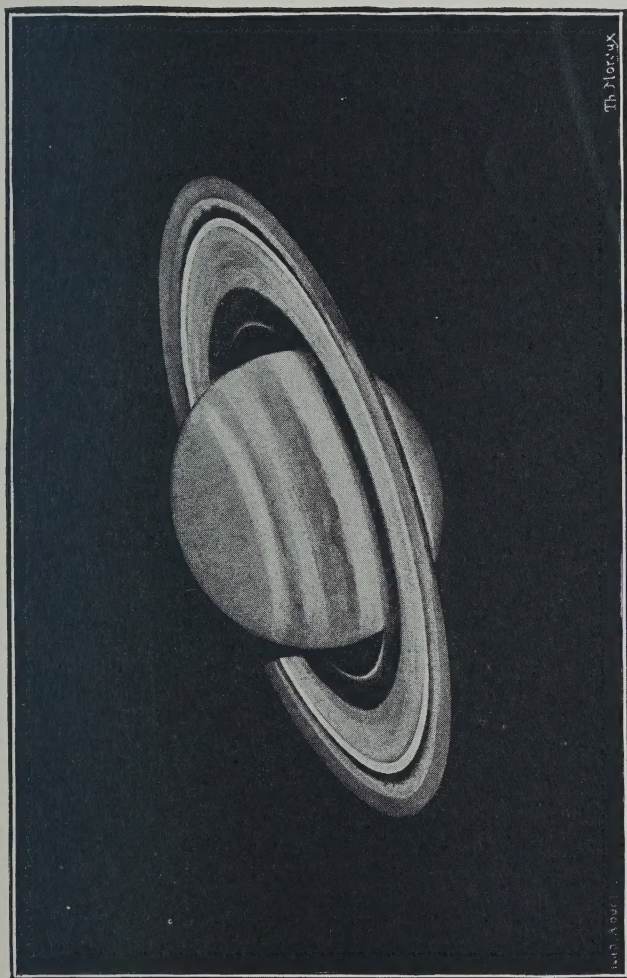


FIG. 42.—THE PLANET SATURN WITH ITS RINGS
(From a drawing by the Abbé Th. MOREUX, at the Observatory of Bourges)

and when powerful telescopes are employed a thin luminous line never ceases to be visible. Observations of this kind, as well as the consideration of the shape of the shadow which is cast by Saturn's globe upon the rings, have shown that the thickness of the structure is by no means uniform throughout its whole extent. In the dark or crape ring the thickness is exceedingly small, but it increases rapidly in the middle one and attains its maximum value a little short of Cassini's division. The outer ring seems on the whole more uniform, but even here there is a thinning-out in the middle of its breadth, corresponding to Encke's division. Schär, at Geneva, has observed in addition a nebulous fringe which makes the outermost boundary of this ring A, and other observers claim to have seen something of the kind; but definite confirmation is as yet lacking, though from the theoretical point of view there is nothing unlikely in such a phenomenon.

Thus it is not possible to assign a single value to the thickness of the rings, and all that can safely be asserted is that it is between 40 and 90 miles. The relative value of this will be brought out more clearly by the following comparison: if the globe of Saturn is represented by a sphere measuring one foot in diameter, then on the same scale the thickness of the rings will be represented by that of a sheet of paper.

What is the constitution of the rings? The question is one of the deepest interest, but it was not until the middle of the nineteenth century that a satisfactory answer was given, through the researches of Roche, Maxwell and Hirn.

Rings which were either gaseous or liquid would have been slowly drawn nearer to the planet and would long ago have been incorporated with the main body; while an entirely solid structure would rapidly have suffered the fate of being shattered to pieces. From the mechanical point of view, therefore, the only possibility is that the

rings are composed of small particles. They may be compared with a swarm of meteors, each of which is really a satellite revolving separately on its own account.

Even J. D. Cassini in 1705 had suspected this to be the truth of the matter. "This ring," he wrote, "may possibly be formed out of a swarm of small satellites, the appearance of which, as seen from Saturn, would be similar to that of the Milky Way, with its innumerable multitude of small stars, as seen from the Earth."¹

If this is the true constitution of the ring, the corollary follows at once that in accordance with Kepler's laws the interior particles must revolve more quickly than those nearer to the external circumference. To verify such a state of things is not easy, yet it should be possible to do so by carefully watching the spots or knotty protuberances on the ring. Unfortunately, few observations of this sort are available; nevertheless, spectroscopic methods of investigation have yielded results which leave the matter in no doubt since the experiments of Keeler in 1895.² The periods of revolution of the particles obey the third law of Kepler very closely: for the outermost parts of the ring the period must be 13 hours, and for those at the internal boundary it must be no more than 5 hours 30 minutes. The latter, therefore, revolve more quickly than the equatorial part of Saturn's surface.³

We may note in passing that a result of this kind is not exactly calculated to gratify those persons who still try to defend Laplace's theory of cosmogony. It will be remembered that in the opinion of that eminent geometer the planets came into being as a result of the breaking up of rings which had been detached one after another from a rotating sphere, and the satellites were formed out of their

¹ See "Mémoires de l'Académie," 1715, p. 47; MONTUCLA, *Histoire des Mathématiques*, t. iv., p. 19.

² "Astrophysical Journal," I, p. 416.

³ These results have been confirmed by Campbell, Deslandres and Belopolsky. The values obtained by the spectroscope for the periods of rotation are slightly different from those given above, but this can be explained by the difficulty of making accurate measurements by means of so delicate a process, in the case of very small radial velocities.

planets in a similar manner. An illustration of the theory was found in Plateau's famous experiment with the drop of oil ; such a drop, it was said, though originally spherical, becomes flattened as it rotates, and takes the shape of an ellipsoid of revolution ; but the flattening process cannot be continued indefinitely, and after a time the acceleration causes the swollen part round the equator to be detached in the form of a ring. This may either break up, in which case we get the formation of a satellite, or it may somehow persist, and then it exactly represents the appendage by which Saturn is accompanied.

But it is just at this point that the illustration fails us ; for, if the law of areas is to hold good, the ring must rotate more slowly than the sphere from which it separated itself, and the same is true also for a satellite. Now we have seen that this is not so in the case of the inner satellite of Mars, or in that of the Saturnian ring. We are therefore compelled to conclude that neither of these two is derived from its planet in the way that Laplace indicated.

The fact is that the small particles of which the ring is composed have never formed part of the globe of Saturn. Rather, they are made out of the materials of a satellite that was still-born, never being able to achieve its own formation. This view is confirmed, moreover, by the theoretical conclusions of Roche, who proved that it was impossible for a satellite to exist nearer to its primary than a fixed distance of 2.44 times the latter's radius.¹

To return, however, to the constitution of the ring, the theory that it is nothing but a swarm of satellites has done something more than merely hold its own against attacks, it has also succeeded in furnishing an explanation of the gaps and congested regions which have been observed in the structure. Both seem to be in accordance with the famous law of commensurability which Kirkwood² put forward in relation to the distribution of the asteroids.

¹ The exterior boundary of the ring is at a distance of only 2.289 times the radius of Saturn.

² *Meteoric Astronomy*, chap. xii, 1871.

When the period of revolution, which a particle would have, can be shown to be related in a simple manner with those of the first four satellites, a gap occurs ; and it can be calculated that the rarefaction required by this theory attains its maximum exactly at the distance of Cassini's division. This gap therefore seems to be the only one possessing a permanent character ; in all other regions the perturbations are cancelled to some extent, and as in the case of the asteroids the gaps are never either complete or constant.¹

There is still one point which needs to be elucidated. The total mass of the ring is insignificant, if one may judge by the very slight disturbance which it produces in the movements of the satellites. But a layer of meteorites extending in the form of a corona whose breadth was more than five times the Earth's diameter, would certainly, even if it had little thickness, represent an appreciable quantity of matter. Here, then, is a startling contradiction. It may be replied that, to judge by their brightness, the particles of the ring are assuredly not of the same metallic or stony composition as the meteorites that fall on to the Earth ; but this only puts the difficulty a little farther back.

The observed results seem to require that the particles should be specifically so light as to approximate to masses of gas, yet we have seen on other accounts that such a hypothesis cannot be entertained. The contradiction would perhaps disappear if we were to admit that each little spherical satellite is entirely distinct from its neighbours, and is very far as yet from having attained its final stage of condensation. It would seem to consist of a nucleus somewhat more advanced in that direction, surrounded by an atmosphere of correspondingly small dimensions. This explanation was suggested to me by the fact that some satellites are actually known to exist in such a state ; for example, the four large satellites of Jupiter, whose albedo is comparable with that of their primary—a sure

¹ See also MAYER : *Astr. Nachrichten*, No. 2527.

indication that their constitution is similar to that of the planet itself.

Whatever the solution of these difficulties may ultimately prove to be, we must at any rate recognise that the ring has a relative stability great enough to guarantee that it will exist for a long time, without however safeguarding it absolutely from the risk of future disruption. Was it not Struve who announced in 1851 that the ring was gradually getting nearer to the planet? In three centuries, he was convinced, it would have disappeared completely. Recent measurements have certainly not tended to confirm this gloomy prediction.¹

The phenomenon of the ring's approach is merely a matter of periodic variation, the conditions of which have been ascertained. Like the orbits of the planets, the trajectories of the millions of satellites which make up the whole structure are subject to deformations which resemble those undergone by an elastic ring. The movements in the whole mass are, moreover, exceedingly complex; the most eccentric were soon eliminated, yet those which still persist are not strictly circular, as is proved by the fact that the globe of Saturn is not at the exact centre of the rings—indeed, so far is this from being the case that, as seen from the Earth, the ring does not always project symmetrically on the two sides of the planet! Here, then, is a mechanism of very great complexity, and even that is nothing in comparison with the difficulties which baffle any attempt to explain the origin of this remarkable structure.

Prodigal as nature has shown itself in furnishing such an appendage for a planet which is not so big as Jupiter, the result has not by any means exhausted the supply of materials available for the formation of its satellites. There are no fewer than ten moons which accompany Saturn on its stately and majestic revolution.

The largest of them, Titan, was discovered by Huygens

¹ See BARNARD's observations (1895) in "Monthly Notices," vol. lvi, p. 163.

in 1655; its diameter measures a little more than 2,200 miles, or about 70 miles more than that of our Moon. All the satellites have been given names from ancient mythology, and the list of those which have been longest known, commencing with the one farthest from the planet, is as follows: Japetus, Hyperion, Titan, Rhea, Dione, Thetys, Enceladus, Mimas.

In 1904, W. H. Pickering announced the existence of Themis, between Titan and Hyperion. All these nine are direct, but that is not the case with the most distant one, Phoebe, which the same astronomer had discovered in 1898. This satellite, which takes about 550 days to accomplish its revolution, at a distance of more than 8,000,000 miles from its primary, moves in the retrograde sense, and its discovery was the occasion for the capture-theory to be revived. We have seen what to think of that theory, in our discussion of the last two satellites of Jupiter.

The attempt has often been made to formulate, for the distances of satellites, a law analogous to that which Bode gave for the planets, but it has never been successful. In particular, no one has been able to explain how it is that we find in both Jupiter's and Saturn's systems a pair of associated moons whose orbits are so nearly the same. This was the case with Jupiter's satellites VI and VII, and it is even more strikingly so with Hyperion and Themis, for which the periods of revolution differ by no more than a few hours from a mean value of 21 days.

It is evident that those who are devoted to the study of cosmogony are in no immediate danger of suffering from enforced idleness, for lack of sufficient problems to keep them busy.

CHAPTER IX

THE PLANETS URANUS AND NEPTUNE

FOR thousands of years mankind was convinced that the solar system was bounded by the orbit of Saturn. Beyond that was the region of the fixed stars, and no one had ever imagined how immense their distances were ; indeed, some astronomers were persuaded that Saturn's shadow might sometimes hide from us certain of the stars in the zodiac. But the extent of the Sun's domain was destined to be doubled, at one stroke, by Herschel's discovery of a new world.

Too poor to purchase the optical instruments which he wanted, William Herschel set himself to construct his telescopic mirrors with his own hands, and he had no sooner completed one of 6 inches aperture than he began his second survey of the heavens with a magnifying power of 227. On March 13, 1781, between 10 and 11 o'clock in the evening, he was examining some small stars in the constellation Gemini when his attention was attracted by one which seemed to possess an appreciable disc. With more powerful magnifications this disc increased in size, but at the same time, unlike the neighbouring stars, it lost its sharpness of definition ; a little later it became clear that it was altering its position and was animated by a movement of its own. Planet or comet, which was it ? Herschel decided in favour of the latter alternative, and it was under the title of *Observations of a comet* that on April 26, 1781, he modestly communicated his discovery to the Royal Society. The news had been known since April 16, and astronomers everywhere were busy trying to fix the elements of the new comet, but it obstinately refused to follow the parabolic path in which they considered that it ought to be moving.

At length, on May 8, 1781, Bochart de Saron, who was only an amateur astronomer, declared that all their efforts would be fruitless until they assumed for the new body an elliptical orbit, with its perihelion radius at least equal to fourteen times the Earth's distance from the Sun. Not long afterwards Lexell and Laplace went further, and asserted that the orbit of the new star must be very nearly circular, and that its radius must be at least nineteen times the distance from the Earth to the Sun. From that moment it was plain that a new planet had been discovered.

Herschel had taken no part in this discussion, but he claimed nevertheless—and justly—that he was entitled to choose a name for the new star, and he called it *Georgium Sidus* (the star of George) in honour of King George III. Lalande wished it to be called by the name of its discoverer, but in the end the advice of Bode prevailed and the seventh planet received the name of Uranus.

When the first wonder was past, people began to ask how it was possible that a star of the sixth magnitude, which was therefore easily visible to the naked eye, should have escaped observation by earlier astronomers; it could not be accounted for by large variations in its brightness, since the orbit was nearly circular. Investigations then showed that the new planet had in fact been previously seen by numerous astronomers, but that it had been entered in the catalogues as an ordinary star.¹ One observer, Lemonnier, had himself seen it at least a dozen times.²

At its mean distance Uranus is almost 1,800 millions of miles from the Sun, and its distance in aphelion exceeds this figure. Its mass is nearly 15 times as great as the Earth's, but its huge volume shows that it is to be classed

¹ An examination of the catalogues reveals that Uranus had been noted as an ordinary star in 1690, again in 1712, then three times in 1715, once by Mayer in 1756, and so on.

² In this connexion Arago remarks in his *Astronomie populaire* (p. 489) that Lemonnier's records of his observations were in a state of chaos: "Bouvard once showed me that one of the observations of the planet Uranus was recorded upon a paper bag which had originally contained hair-powder, bought at a perfumer's shop."

among the planets of low density. At such a great distance observation becomes very difficult ; the disc seems much flattened (the ratio being about $\frac{1}{13}$), but measurement of the equatorial radius is a task of considerable delicacy, and this explains the lack of agreement between the values which have been given at different times. A study of recent observations, corrected for irradiation, has led me to adopt 30,500 miles as the length of the equatorial diameter, which would make the planet's volume 52 times greater than that of the Earth ; and as its mass is known very exactly from the movements of its satellites, it would then follow that its density was 1.54.

There is still much uncertainty as to the physical aspect of the planet ; different investigators have noted belts of a not very pronounced or well-defined sort, but their observations have not sufficient agreement to warrant our drawing precise conclusions. Thanks, however, to the use of those spectroscopic methods to which we have already alluded in the chapter on Mercury (p. 40 *supra*) Slipher has recently found the period of the rotation of Uranus to be 10 hours 45 minutes, and this rotation is retrograde like the revolution of the planet's satellites.

These satellites are four in number. The two largest, Titania and Oberon, which are the farthest distant from the planet, were discovered by W. Herschel in 1787 ; the others, Ariel and Umbriel, whose orbits are nearer, were discovered only in 1851, by Lassell. They are all small bodies with diameters varying between 400 miles (Umbriel) and 800 miles (Titania) ; they appear all to revolve in the same plane, and—what is very remarkable—their movement, as we have just said, is retrograde ; their orbital plane is inclined at an angle of 82° to the ecliptic, and coincides with the equatorial plane of Uranus.

As soon as astronomers had recognised the nature of the planet's orbit (of which the eccentricity is only 0.04), the next task was to apply to it the laws of celestial mechanics. For this purpose it sufficed to make use of the earlier observations which, as we have already seen, extended

back for a considerable time, the first of them dating from 1690. But it was soon perceived that the planet's motion exhibited inexplicable irregularities.

Alexis Bouvard had drawn up very complete tables fixing the positions of Uranus, but the planet persistently refused to conform to Kepler's laws, and the astronomer was so much discouraged that he wrote in 1821, "I leave it to the future to show whether the difficulty of harmonising the two systems is really due to the inaccuracy of early observations, or whether it is due to some strange and at present unknown force acting upon the planet and influencing its movement."

After a short time Bouvard's tables had come to differ so seriously from the observed facts that in 1829 Hansen believed that the only way to explain the divergence was to suppose that the movement of Uranus was influenced by two unknown planets. Some scientists took advantage of the situation to express doubts as to the validity of the law of gravitation. At one time Bessel himself was inclined to this opinion, but he soon returned to a more sensible view, and in a letter to Humboldt (which is quoted by Arago) he wrote the following characteristic sentence: "The time will come when the problem will perhaps be solved by the discovery of a new planet, whose elements will first of all be determined by its effect upon Uranus, and then verified by the influence which it exerts upon Saturn." To put the matter shortly, the general opinion by 1845 was such that Arago strongly advised Le Verrier to investigate the problem thoroughly from this point of view. And in less than a year, the young mathematician had overcome all the difficulties which were involved, and pointed out the exact position which must be occupied by the "disturber" of Uranus.

Such phrases as "lucky chance" have so often been used about Le Verrier's great discovery that we must not pass over in silence the way in which he went to work to obtain the solution of the problem—one of the most intricate that has ever been confronted. I will therefore

try to give some idea of the method which had to be followed.

We have seen that the heavenly bodies are subject to a great number of perturbations, due chiefly to their closest neighbours, and that these cannot be neglected. When Jupiter, for example, happens to be in conjunction with Saturn,—that is to say, when they are both on the same side of the Sun and in the same direction,—the large planet attracts the smaller one towards itself; and as it revolves more rapidly, through its solar distance being less, it tends to drag the other in its own direction, so that the movement of Saturn is accelerated and its orbit is deformed. From this it follows that, as seen from the Earth, Saturn must occupy a different position from that in which it would have been if it were revolving round the Sun all by itself. It can therefore be understood how a skilful mathematician, even if he were entirely ignorant of Jupiter's existence, might nevertheless deduce from his observations of the positions of Saturn both the existence and the mass of the planet which was causing the irregularity.

It was by considerations of this sort that Le Verrier had to be guided in his search for the unknown planet which perturbed the movement of Uranus, but the problem in this case was still more complicated. It was necessary first to trace out the orbit which Uranus would accomplish once in every 84 years, taking account of those perturbations which were produced by its known neighbours, especially the two big planets Saturn and Jupiter. In other words, it was necessary to assign to Uranus for every instant, both in its modified orbit and in the heavens, a fictitious position depending on its own proper motion and on Saturn's and Jupiter's influence. The disagreement between this fictitious calculated position and the one which Uranus actually occupied according to past and present observations had to serve as the basis for the new investigations. After long calculations this residue as we may call it, consisting of the perturbations which had

to be attributed to the unknown mass, was actually obtained.

Where was this mass? In what direction should it be looked for? How big was it? There was no possibility of using exact data in order to arrive at the answers to these questions, for none were available. So hypotheses had to be employed, and Le Verrier assumed first of all that the orbit of the disturbing planet conformed to Bode's law; he could not, he thought, be far wrong in placing it at a distance from the Sun equal to twice that of Uranus. Again, the large planets exterior to the Earth in the Solar system are never removed from the plane of the ecliptic by more than two degrees, and he regarded this as a sufficient reason for assuming that the unknown planet was in this plane. Finally, he supposed that the eccentricity of its orbit was small, and that its mass did not differ greatly from that of Uranus.

When simplified to this extent, the problem did not involve more than eight unknowns; but, ignorant as the great geometer was of the planet's direction in the heavens, he was obliged to divide its probable orbit into forty different sections, and work out for them forty different solutions. That one would be judged correct which accounted for the observed perturbations most satisfactorily.

The work was begun in 1845, and it took only eleven months to complete it. On August 31, 1846, Le Verrier announced to the Académie that the looked-for planet would be situated, on the first of January next following, in true longitude $326^{\circ} 32'$. The conclusion of his Memoir was as follows: "In 1758 Clairaut spoke of planets which were so far off that they would never be seen. Let us hope, however, that they will not always remain invisible; and that just as Uranus was accidentally discovered, so we shall actually succeed in observing this new planet whose position I have now made known."

In order that my readers may have some idea of the labour involved in researches of this kind, it may be added

that the theory of the perturbations of the four large planets, Jupiter, Saturn, Uranus and Neptune, fills no less than five huge volumes containing altogether about 2,300 pages; while the subsidiary calculations, which have not been printed, amount to a total three or four times more lengthy.

It has been urged as a reproach against this distinguished mathematician that he addressed himself in the first place to a German astronomer with a view to a search being made for the planet; but the story is an invention. The true account, however, did not become known until 1905, after the death of Dr. Galle, the director of the Berlin Observatory, whose examination of the region of the heavens which Le Verrier had indicated resulted in his discovering Neptune. What actually happened may be briefly set down here.

In 1846 Galle had sent to Le Verrier a memoir dealing with one of Römer's papers, and on September 18 of the same year Le Verrier wrote to him to express his thanks. At the end of his letter he told him incidentally of the work in which he had been engaged. The passage is as follows: "Just now I am anxious to find an indefatigable observer who would be willing to devote some time to the task of examining a region of the heavens in which there may possibly be a planet awaiting discovery. I have been led to this result by the theory of the movement of Uranus. Some of my investigations will be published shortly in the *Astronomische Nachrichten*, and so I should not have needed to write to you on the subject if it had not been that I felt bound to thank you, Sir, for the interesting work which you have sent me.

"As you will see, Sir, I prove that the observed positions of Uranus cannot be satisfactorily explained except by introducing the action of another planet, hitherto unknown. And it is a remarkable circumstance that there is only one position in the ecliptic which can be assigned as the location of this disturbing body. (Then follow the astronomical elements of the planet.)

“The present position of this star shows that the conditions are now, and will be for several months to come, favourable for its discovery. Moreover, we may conclude from the greatness of its mass that the size of its apparent diameter is more than three sexagesimal seconds. Such a diameter is quite capable of being distinguished in good telescopes from the fictitious diameters which are given to the stars by various aberrations.

“Pray accept, Sir, etc.”

This letter was dated September 18; Galle received it on the 23rd, and on the same evening he commenced his search and found the planet in the spot indicated; the error was less than a degree—to be exact, 52'. The Berlin astronomer wrote at once (on September 25) to Le Verrier: “The planet whose position you notified to me does actually exist. The very day that I received your letter, I found a star of the eighth magnitude which was not marked on the excellent map *Hora XXI* (drawn by Dr. Bremiker) in the collection of celestial maps published by the Royal Academy of Berlin. The next day's observation showed decisively that it was the planet for which you were seeking.”

So ended “that great task, one of the most amazing and the most original that had hitherto been recorded in the annals of astronomy.”¹ Le Verrier had worthily upheld the reputation of French mathematical astronomy, which scientists like Lagrange and Laplace had already set in the foremost rank.

It would, however, be a grave injustice not to mention here the remarkable achievement of a young English mathematician, Adams, of Cambridge, who had arrived about the same time at a result similar to Le Verrier's. His memoir was earlier than that of the French geometer, for it was sent on September 22, 1845, to Challis, and then got put aside in the drawers of the famous astronomer-royal, Airy, who left it there until the day on which the

¹ Ch. ANDRÉ: *Les planètes et leur origine*, p. 159. Gauthier-Villars, Paris, 1909.

discovery of Le Verrier was made known. To say truth, Airy had not been indifferent to Adams's work, but he was far from being convinced by it, and he put forward certain objections to which no definite answer was received until a year later.

Adams's solution, though less masterly than Le Verrier's, was not less elegant by reason of its simplicity. In fact, if it had been made known in time, it would have been quite adequate. The English mathematician had made the same assumptions that the unknown planet obeyed Bode's law, and that it was close to the ecliptic; but as a first approximation he had taken its orbit to be circular, and by doing so had swept away all the difficulties.

Its distance from the Sun being thus given, the time which it took to complete its orbit was bound to be something like two centuries. Since the first recorded observations of Uranus 155 years had passed, and in that interval Uranus had accomplished nearly two revolutions. It was impossible but that the perturbations which it had experienced during that time, after allowance had been made for those due to Saturn and Jupiter, should exhibit a systematic character that could not fail to be detected. It was therefore simply a matter of finding a definite mass which would accord with these observed irregularities. When this first step had been successfully taken, Adams was able to proceed to the consideration of an elliptic orbit as a second approximation. His final result, from the point of view of the planet's position in the heavens, was almost identical with the one which Le Verrier had obtained.

In other respects, however, the values found by the two mathematicians differed very considerably from the facts. Never had Bode's law been so much at fault, for instead of the number 36 or 37 which Le Verrier and Adams had assumed, or even the number 38 which the series itself indicated, the distance of Neptune is much less than double that of Uranus, and calculation has shown that the much smaller value 30 is the correct one. Thus Neptune

revolves nearer to the Sun than had at first been supposed ; its mean distance is not more than 2,800 millions of miles, and its period of revolution is about 165 years.

Its single satellite, which was discovered almost at the same time as itself by Lassell (on October 10, 1846), is retrograde like the satellites of Uranus, and by its means we can tell the planet's mass with great exactness. It is 17 times greater than that of the Earth, and therefore is only a little more than that of Uranus. Recent measurements of its diameter give a value of 30,000 miles, and this would make its volume about 60 times greater than the Earth's, and its density 1.55.

Neptune would therefore seem to be a little larger than Uranus, but to have the same density ; and as in the case of all the exterior planets this small density indicates a gaseous constitution and a high temperature. We have to be satisfied with what we can learn from these figures, for in the case of so distant a planet exact conclusions based upon direct observation are not possible. It is true that in 1899 See noted the existence of an equatorial belt of clouds, which he said occupied just the position which theoretical considerations would lead one to expect, but Barnard, using the powerful telescope of the Lick Observatory, was never able to distinguish any phenomenon of the kind.

In discussing the observations which have been made of the movements of Neptune's one satellite, Tisserand and Newcomb arrived independently at identical conclusions. It retrogrades in an orbit whose plane is inclined at 38° with the ecliptic and at 20° with the equatorial plane of its primary. The planet is flattened to only a slight extent ($\frac{1}{85}$) ; yet, according to the recent calculations of MM. Opik and Livlander, of the Dorpat Observatory, its rotation is rapid, and takes place (probably in the retrograde sense) in 7 hours 45 minutes. This result agrees very well with the observations of Maxwell Hall, who in 1883-84 asserted that the period of Neptune's rotation was in the neighbourhood of 8 hours.

Just as in the case of Uranus, a search among past records, made after the new body had been discovered, revealed the fact that Neptune had already been observed at different times ; but, like Uranus again, it had been taken for an ordinary star. Gore asserts that a study of Harding's Atlas (1822) might well have led to a discovery of the planet, for it figures there as a star of the eighth magnitude which could be seen through an opera glass. In any case it is quite certain that Lalande registered it as a star on May 8 and 10, 1795.

These observed positions are of importance for us to-day, and in the future will become even more so, for the purpose of studying the perturbations by which it is already evident that Le Verrier's planet is affected. It may be that they will even furnish future geometers with the means for discovering another planet beyond Neptune, the existence of which has several times been suspected. Hitherto, however, all efforts at the discovery of such a body have been in vain, and the considerations which have been put forward on the subject are of so speculative a character that any definite solution of the problem seems still a long way off. We shall return to it in our discussion of the periodic comets.

Now that our survey has brought us to this farthest point of the solar system, let us look back from it towards the different bodies which we have hitherto been considering. From this remote world, Mercury, Venus, the Earth and Mars would be invisible, through being lost in the light of the Sun. Even Jupiter could be seen only at the time of its transits across the solar disc, when it would appear as a very small black spot. Saturn would be to the inhabitants of Neptune, if they existed, only what Mercury is to us, and at favourable epochs would barely possess the brightness of a star of the sixth or seventh magnitude. Uranus, the nearest neighbour among the planets, would shine as brilliantly as Sirius does for us in our winter skies.

To the naked eye the Sun would have no apparent disc,

and its appearance would be comparable with that of a good-sized arc lamp; it would, however, be bright enough to illuminate the cloudy surface of Neptune as much as an electric light of a thousand candle-power would do if placed only a few yards away. Its light would have taken more than four hours to traverse the long interval separating the two bodies. It is only by such considerations as these that we can get any idea of the vast distances which it is the task of astronomers to measure. What degree of accuracy is it possible for them to reach in such circumstances? That is the question which we have to consider in our next chapter.

CHAPTER X

THE PROBLEM OF DISTANCES IN ASTRONOMY

IN order to deal with the immense distances which have to be calculated, astronomers need a large unit of length. The distance between the Earth and the Sun was chosen long ago for this purpose, and it constitutes the unit for astronomical measurements.

Since the time of Kepler, as we had occasion to remark in connexion with Wolf's or Bode's Law, the relative distances of the various planets from the Sun can be ascertained with very great accuracy; in fact, they can be deduced from the periods of their revolutions. If we state them in terms of the astronomical unit, we get the following figures (correct to two decimal places):

Distance from the Sun to	Mercury	..	0.38
"	"	"	Venus 0.72
"	"	"	the Earth .. 1.00
"	"	"	Mars 1.52
"	"	"	Jupiter .. 5.20
"	"	"	Saturn .. 9.55
"	"	"	Uranus .. 19.21
"	"	"	Neptune .. 30.10

These figures are absolutely independent of the value of the unit of length, but they do not enable us to do more than construct the *plan* of the solar system. The *scale* of the drawing still remains to be found, and for this purpose it is clear that we must find the actual value of the unit distance. Thus everything depends, as the reader will now readily understand, on the calculation of the distance between the Sun and the Earth.

CHAPTER XI

THE COMETS

BESIDES the planets and their satellites, there exists in space an incalculable number of other bodies which are subject to the Sun's attraction, and which in the past, when little was known about them, were all classed together under the general title of meteors. These are the comets, shooting stars, and meteorites; and the most important are the comets.

Kepler said of these bodies that they were more numerous than fishes in the sea, and indeed it was no exaggeration. Our catalogues give rather more than a thousand, and about half of these have been recorded since the invention of telescopes; not all comets are visible to the naked eye, and we are now able to detect many more than was formerly the case. Having regard to the most recent figures, it may be asserted that in the course of 2,000 years about 3,200 comets can be observed; but that figure represents a bare minimum, for the fact is that our observation of these stars depends upon their perihelion distances being small enough to bring them within our field of vision. If we take account of the rest, and make the assumption that the distribution is uniform, we arrive at the figure 44 millions for the number of comets which may be revolving so as to approach within the orbit of Neptune; and this would be increased to more than 200 millions if we were to include all those which come within the sphere of the Sun's attraction.

These figures make no claim to represent the facts accurately; and they take for granted a regular distribution which, while it is probable enough, is far from being proved. Further, it is to be remarked that until

quite recently the origin of the comets, or, to speak more precisely, the nature of their orbits, constituted a problem beyond the hope of solution.

We are now beginning to rid ourselves of the ideas which were so dear to astronomically-minded poets, who liked to speak of comets as "messengers from the infinite." Our views on the subject are possibly more prosaic nowadays, but they are not on that account less interesting; unfortunately, however, they have by no means as yet penetrated into the minds of ordinary people, who are likely for a long time to go on being misled by the distorted representations of popular writers.

Let us first explain as precisely as we can the present state of the question. We have already seen that under the controlling attraction of a central mass, a material particle is bound to describe a conic—that is to say, a circle, ellipse, parabola or hyperbola. The comets are no exception to this rule, but on account of their diffused aspect their trajectories are not always easy to fix. For some of them, however, there can be no uncertainty in the matter; the orbits are undoubtedly elliptic, as is proved by the fact that they return to us after a longer or shorter interval which constitutes their period of revolution.

It may be that all the rest are periodic too, but it is desirable that this should be proved. The whole question comes to this: are their paths hyperbolic, parabolic, or elliptic? In the first two cases the comets would be, not regular members of the solar system, but strangers which had for once found their way into it; and it is important for us to decide whether such cases exist. Now, even with the help of exact observations this seems a difficult matter to settle, and the reason is that in the region where they come within range of our observation, the arcs of the different conics differ from one another to only an infinitesimal extent. On the whole, however, investigations show that few orbits actually exhibit the hyperbolic shape; instead, there is clearly manifested a tendency towards

the parabola. This is a circumstance which ought to exercise the minds of astronomers, for we know that there is no chance of such a curve being realised in nature ; it is, in fact, a limiting case, just as is the circle. When we consider this it becomes clear that there are really only two alternatives for us to choose between—the ellipse and the hyperbola.

Since it has been ascertained that the Sun is itself moving at the rate of a dozen miles a second, it has become

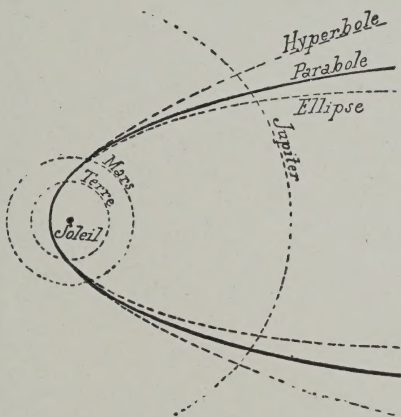


FIG. 45.—FIGURE TO ILLUSTRATE THAT THE ARCS OF THE DIFFERENT KINDS OF CONICS ARE ALMOST IDENTICAL NEAR THE FOCUS (THE SUN), IF THE PERIHELION DISTANCE IS THE SAME

more profitable to discuss the problem of the comets, and investigations have been carried on by astronomers like L. Fabry, Stromgren and Fayet. Let us suppose that bodies foreign to our system are brought within the sphere of the Sun's attraction as a consequence of our movement. Then, even if we attribute to them a very small velocity of their own, their relative motion would still be too great for an elliptic path, and it can be shown by calculation that all comets originating in this manner would be obliged to describe hyperbolas. This does not at all correspond with the facts, and we are therefore

driven to believe that these stars have always formed a part of the solar system.¹ But if this is so, it remains to be explained why certain comets—though, it is true, not many—do move in hyperbolic paths. Are not these at any rate exceptions to the general rule?

The problem has been studied very thoroughly during recent years by my friend L. Fabry of the Marseille Observatory; and his conclusions, though as yet little known, deserve to be carefully considered by all who are interested in the subject. In a memoir which received the honour of recognition by the Académie, this learned astronomer has discussed the case of the ten comets which are most pronouncedly hyperbolic, and has proved that their original orbits do not present any such character.²

“If the orbits which these comets describe around the Sun,” he writes, “are slightly hyperbolic in the neighbourhood of perihelion, that is solely due to the perturbations caused by the planets. By the attraction which they exert, the planets, and especially Jupiter and Saturn, increase the speed of these comets to a small extent; and the result is that by the time they arrive near perihelion the speed slightly exceeds the parabolic velocity which would be appropriate to the Sun’s mass considered as the sole attracting body.”³

Thus the orbit becomes an arc of a hyperbola in that part which we see, whilst at aphelion and at a great distance from the Sun it consists of an ellipse which is so much elongated as to approximate very closely to a parabola.

The study of the question has been taken up more lately by Fayet and Stromgren, and though their methods are different from M. Fabry’s the conclusions at which they have arrived are identical.⁴

In opposition to these very definite conclusions, a fact

¹ This conclusion is diametrically opposed to the ideas of Laplace.

² L. FABRY: *Étude sur la probabilité des comètes hyperboliques et l’origine des comètes*. Paris, 1893.

³ *Notice sur les Travaux scientifiques de M. L. FABRY*, p. 29. Gauthier-Villars, Paris.

⁴ “Bull. Soc. astr. de France,” October, 1919; “Scientia,” August, 1918.

has been urged which is at first sight highly characteristic of comets in general. That comets do actually come from other systems into ours is proved, it is said, by the tendency of their perihelion positions to be grouped in a manner which depends upon the direction of the Sun's own movement ; or we may put it in this way, that the comets come to us chiefly from that part of the heavens in which the chance of our meeting them is greatest.

But this is simply an illusion, or rather, as an argument, it is inconclusive. M. Fabry shows that the true explanation of the fact must be looked for not in the direction of the Sun's motion, which moreover would not lead to such a result at all, but in the respective positions of the ecliptic and the horizon of our observatories at different times of the year.¹ Indeed, we may say more ; statistics of the different comets do not show a single trace of the proper motion of our system, and the conclusion is therefore forced upon us that they belong to it permanently.

All the comets, then, travel in elliptic orbits, but some of them have their aphelion positions so far distant that there is time for several generations to pass away, and the strange visitors to be completely forgotten long before they come back again. Such would be the case with the famous comet of Donati which appeared in 1858 ; its period is 1,950 years, so that its next appearance will take place in the year 3808. We can therefore no longer maintain the distinction between periodic and non-periodic comets. The most that we are entitled to do is to distinguish between the ones whose return has actually been observed and those which have only been known to appear on one occasion.

The orbits of even the former class have both axes very large, and their eccentricities range from those of the minor planets to values very close to unity, in which case they approximate to parabolas. When it is stated further that the inclinations of the planes of the cometary orbits to the ecliptic have almost every possible value, up to

¹ See *Notice sur les Travaux scientifiques de M. L. FABRY*, p. 26.

even 90° , it will be easily comprehended that from the mechanical point of view there is no real gap between the planets and the comets.

The fact is that from the former, with their direct and almost circular revolution in planes but slightly inclined to the ecliptic, we pass to the latter by way of the asteroids. We have seen already, in the chapter which was devoted to the minor planets, that several of these have greater eccentricities than some of the comets, while in one case the plane of motion is inclined to ours at an angle of 48° . Thus the transition from the planetary world to that of the comets is made by insensible gradations, especially if we accept the convention by which bodies are regarded as retrograde when their orbital planes make angles larger than 90° with the plane of the ecliptic.

Among the periodic comets, however, retrogression is a comparatively rare phenomenon. Out of 48 whose return has been observed without any doubt and whose aphelion distances range from 4 to about 200 astronomical units, not more than 8 can be counted as retrograde. If we consider those whose aphelia are distant from 4 to 800 astronomical units, 25 out of 81 are retrograde. The larger number in the second case brings into prominence a cause which must have been in operation from the beginning of the formation of our nebula, namely the tendency of the planetary masses to collect around themselves by means of their attraction the numerous bodies which move in their neighbourhood, especially those whose planes of motion are but slightly inclined to their own.

We are thus led to the consideration of *families of comets*. No one who concerns himself with cometary statistics can fail to be struck by the very noticeable case of such a grouping in the neighbourhood of Jupiter's orbit. In the course of its slow revolution and by reason of its eccentricity this great planet sweeps out a circular path within limits ranging from 4.9 to 5.5 astronomical units; and as the centuries have passed the region near its orbit has passed under the control of its powerful attraction. The

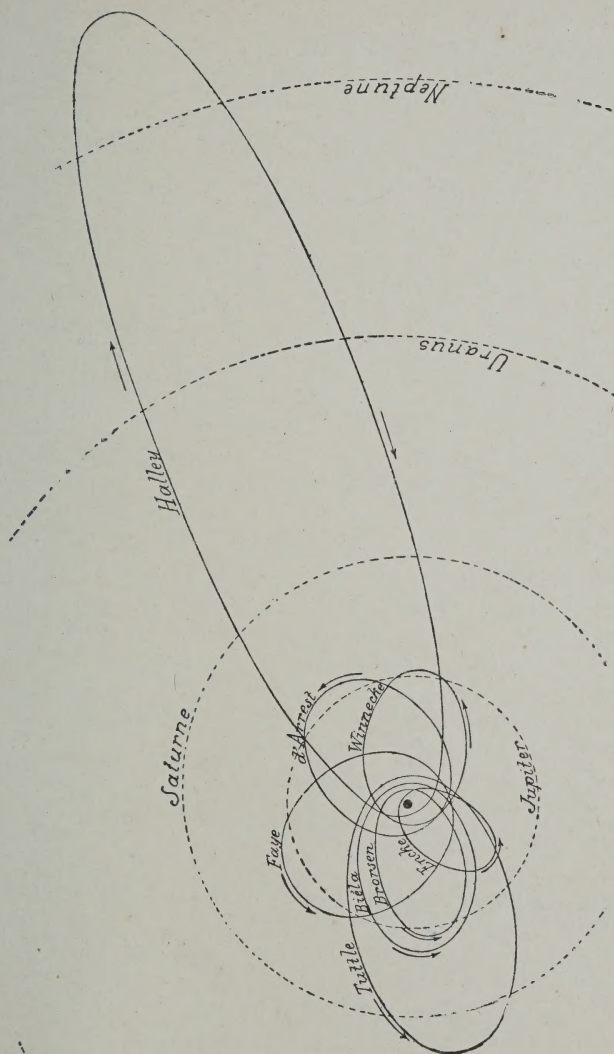


FIG. 46.—ORBITS OF THE PRINCIPAL PERIODIC COMETS

comets which would otherwise have scarcely travelled outside the orbit of Mars have been compelled, when in aphelion, to submit to the pull of Jupiter and to move to some extent in its direction. In the same way, those which would otherwise have extended their paths a great deal farther have been checked in their journey, so that in their case also the aphelion position is brought nearer to the position of the planet.

There are, in fact, seventeen periodic comets whose aphelia are distant from 4.09 astronomical units (Encke's comet) to 6.22 (Biela's). In view of this, the effect of Jupiter is manifest. Have these comets been captured when passing near our system, as the earlier astronomers believed? What we have said already in regard to the capture-theory makes such a hypothesis exceedingly unlikely. It is much simpler, as well as more natural, to suppose that the materials out of which they are composed are a continuation of the series of asteroids with which they have so much in common. The one whose plane is most steeply inclined to the ecliptic is Giacobini Zinner's, for which the angle is not quite 31° . They are all direct in their movement, and they form the group known as the *Jovian family of comets*.

To proceed to the conclusion that the more distant planets exerted a like influence upon other comets is only a step, and astronomers have not hesitated to take it; but it must be confessed that in this case the assumption has been a less happy one. As a rule, account has been taken only of aphelion distances, and this explains why certain writers have imagined the existence of a family of comets associated with Saturn, on the ground that Tuttle's comet had its aphelion at the same distance as that planet. They have taken no notice of the fact that its inclination is exactly 55 degrees! In such conditions it is something more than absurd to suppose that Saturn's influence has determined the comet's aphelion.

There can be no doubt that some comets, whose orbits are only slightly inclined to the ecliptic, have been affected

by the action of Uranus or Neptune ; for example, the comet known as 1867 I and those of Brorsen and Halley, for which the angles of inclination do not exceed 20 degrees. But it would be very unintelligent to suppose that a comet like de Vico's, with an inclination of 85° , could have had its aphelion determined by Neptune which moves in a plane almost at right angles with its own !¹

The same may be said in regard to the comets outside the orbit of Neptune, a list of which has recently been given.² Here again we have to do with inclinations which reach as much as 79, 85, and even 87 degrees ; yet it is upon the strength of indications like these that some authors have not hesitated to base their argument for the existence of a planet beyond Neptune, and have even gone so far as to calculate the distance of their imaginary world by the help of such data !

If, then, it is permissible for us to speak of the comets of the Jovian family, it nevertheless seems to me very rash to extend this nomenclature to groups of comets which are altogether different,—unless, indeed, we are prepared to be satisfied with families for Uranus and Neptune numbering not more than two members each.³

We must distinguish carefully between the *families* of which we have been speaking, and the *groups* of comets of which several instances have been observed. This name, "group," is used to designate quite distinct bodies which seem to follow identically the same path, although not at regular intervals of time. This was the case with the comets of 1668, 1843, 1880 and 1882, for which the mathematical elements, though not the physical appearances, seem to have been the same. It may be that in such a case we have to do with a system composed of the materials of what was originally a single comet, which has suffered disaggregation. There would be nothing improbable in

¹ This question is discussed in CHAMBERS' *The Story of the Comets*, p. 40.

² See "Journal des Observateurs," June, 1918.

³ For a further discussion of these questions, the reader is referred to my book : *Origine et formation des mondes*. Doin, Paris.

this, to judge by what we know of the origin of shooting stars ; but the question cannot yet be definitely settled.

We pass now to the study of the physical constitution of these strange objects, and in doing so we find ourselves confronted by fresh problems.

It used to be supposed that a comet consisted of a more or less brilliant nucleus, surrounded by a luminous envelope which was always accompanied by a sort of hairy appendage—the *coma*, from which the name comet was derived. The invention of telescopes has made it possible for us to correct these ideas, at least in part. It is not every comet that is composed of a head, a nucleus, and a tail. Very often the nucleus is lacking, and only a few comets are furnished with that long caudal appendage which used in former days to spread such consternation among peoples.

Many comets are visible only through a telescope, and appear to the astronomer in the form of a small round nebula animated by a motion of its own which is clearly marked in relation to the stars. But it generally happens that as this nebulous mass approaches the Sun, a bright point resembling a faint star is observed, and this is the *nucleus*. Sometimes the latter is double, or even multiple ; the comet of 1882 exhibited seven or eight nuclei, of which the largest measured 5,000 miles in diameter. Sometimes, too, the nucleus is surrounded by several concentric envelopes, like atmospheres of different densities. Sometimes jets of light stream out from the nucleus, and spread away in all directions. The nucleus and the “hair” together form the comet’s head.

It is generally admitted that the nucleus of a comet is composed of a sort of dusty medium, the separate particles of which differ widely in size. It would seem to be a congeries of fragments of sand or rock journeying together through space, each particle being surrounded by a tiny gaseous atmosphere. Such a widely scattered distribution of materials in the nucleus would explain how it is that even the faintest stars are not blotted out

from our sight by the comets ; the stellar light reaches us through the finely divided dust, though it has been noted that it undergoes a certain amount of refraction in the process.

Although the total masses are relatively very small, the dimensions of the nuclei are astonishing ; the smallest ones are 30,000 miles in diameter. And as to the atmosphere which surrounds them, it is in no way inferior, in respect of volume, to the Sun or the stars ; that of Holmes's comet, which appeared in 1892, had a diameter of 1,200,000 miles—nearly 400,000 miles greater than the Sun's.

It will give us some conception of the extreme rarefaction of a medium of this kind if we consider that the mass of the whole is so small as to be inappreciable by any direct measurement. Indeed, it happens not infrequently that the line of a comet's movement makes it graze against some planet ; this has occurred two or three times in the case of the Earth, and in 1886 Brooks's comet passed between Jupiter and the orbit of its first satellite ; yet in these circumstances we have never been able to detect the slightest trace of any perturbation, either of our own planet or of the system of Jupiter's moons, and the only damage has been suffered by the comet itself which has undergone a considerable alteration in its path.

Recent writers agree in stating that a comet's mass could not, at the most, exceed the hundred-thousandth part of the Earth's, and it would probably be nearer the truth if we assigned as the average mass only one-third of this, which would be the same as that of a steel globe 100 miles in diameter. The mean density of such a refined medium must be unimaginably small, far less than that of the most perfect vacuum that we can obtain.

The chemical constitution of the comets has also given rise to interesting investigations. It is plain that we cannot expect to make any analysis of their meteoritic parts, and must content ourselves with finding out what gaseous substances go to the formation of the head and



FIG. 47.—PERTURBATIONS PRODUCED IN THE TAIL OF MOREHOUSE'S COMET (1908). (THE STARS APPEAR IN THE PHOTOGRAPH AS STREAKS, ON ACCOUNT OF THEIR MOTION RELATIVE TO THE COMET DURING THE TIME OF THE EXPOSURE)

tail. Both of them shine with a brightness which is partly intrinsic and partly that of reflected light. We shall return later to consider the effects produced in a mass of gas as a result of its approach to the Sun, but there can be no doubt that we are here witnessing the action of electrical forces, which are continually operating to produce the phenomenon of irradiance by some mysterious process of which we are almost entirely ignorant.

It has been supposed that the Sun's heat is of almost no significance in the production of these phenomena, but this opinion seems to me to be a very unsafe one, widely held though it is among astronomers. When a comet like the one which appeared in 1843 passes through its perihelion at no more than 535,000 miles from the Sun, so that it travels right through the corona, it seems that on the contrary extremely powerful calorific effects must be produced. A good number of comets (eleven at the present time) are in a similar case, with their perihelion distances less than five millions of miles; and of all the comets which are known, 64 per cent. approach nearer to the Sun than the Earth does at its shortest distance. Those comets which move in the neighbourhood of Mercury must experience temperatures above 200 degrees Centigrade.

However that may be, as soon as a comet penetrates into our region of the solar system, the gases with which the nucleus is surrounded increase in volume and become luminous, so that we can determine its spectrum. On such occasions astronomers seize the opportunity which is afforded them of taking numerous photographs. Recent researches by this means, however, instead of leading to definite and harmonious results, have only brought fresh problems into view. The phenomena are of unprecedented complexity, and the questions which they have raised are still a long way from receiving a solution. Our latest knowledge on the subject is thus summed up by a well-known spectroscopist, M. de la Baume Pluvinel:

“Of what bodies are comets composed? A dozen years

ago it would have been a simple matter to answer this question, and I should have said that all comets have approximately the same composition—that they contain on the one hand a hydrocarbon gas and cyanogen, raised to such a high temperature as to be rendered luminous, and on the other hand solid particles which also are incandescent and are capable of being volatilised when brought close to the Sun and so of reflecting the solar light. But to-day, when photographic methods have made it possible for us to extend our investigation over a greater length of the spectrum, the constitution of the comets seems to be much more complex. It is clear at the outset that they have not all the same composition, and when our knowledge is farther advanced we shall be able, no doubt, to classify the comets in different categories in accordance with their spectral type, just as we do already in the case of the stars.

“There are comets which are essentially gaseous, and blue in colour, like Morehouse’s, and others of a yellow tint in which solid particles predominate, like the Johannesburg comet. As regards the nature of the gases which they contain, we can state that they are carbon compounds, but we cannot say that they are necessarily hydrocarbons, as used to be supposed, and it is even probable that they are rather compounds of oxygen. Cyanogen also exists in the heads of the comets, and nitrogen has been found in both the head and the tail.”¹

What has attracted people’s attention to these stars has always been the caudal appendage which they so often draw along with them. The apparent length of this part of a comet varies as much as its actual dimensions. In the Johannesburg comet, which is one of the most recent (1910), the tail measured not less than 30 degrees, and our knowledge of its distance enables us to calculate that its actual length extended to 70 million miles. The beautiful comet of 1811 had a tail 110 million miles long, while the tails of those which appeared in 1680 and 1843 had lengths respectively of 150 and 200 million miles.

¹ “Bull. Soc. astr. de Fr.,” February 1912, p. 59.

As a general rule, the tail is on the side opposite to the Sun, and its direction is that of the radius vector produced ; but it gradually curves away from this radius vector towards the region from which the comet has come, and this frequently gives it the appearance of a large scimitar.

What is the explanation of this ? Plainly it is due to some repulsive action. We have already referred to the pressure exerted by radiation ; this had been suspected by earlier astronomers, but it needed the experiments of Hull and Nichols to provide a positive proof of its existence. These scientists exposed fine particles of dust, falling in a vacuum, to the action of a powerful arc lamp, and succeeded

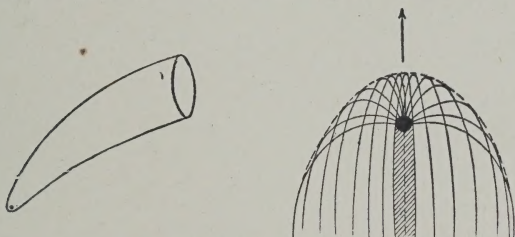


FIG. 48.—(a) THE TAIL OF A COMET IN THE SHAPE OF A HOLLOW CONE. (b) JETS OF GAS BURSTING OUT FROM THE NUCLEUS, AND CURVING BACK TO FORM THE HEAD AND TAIL. [THE ARROW POINTS TOWARDS THE SUN. TR.]

in reproducing experimentally the appearance shown by comets' tails.

The way in which these strange appendages are produced may be described broadly as follows. When a comet gets near the Sun, the molecules of the atmosphere surrounding its nucleus are first of all attracted by the central body, and a sort of tidal movement in the comet is thereby set up. But although this attractive force depends upon the masses, while the pressure of radiation depends upon the surface area, it soon comes about that the latter repulsive force overcomes the former attractive one, and part of the materials composing the concentric envelopes which surround the nucleus are observed to spread away in a backward direction. These materials take with them their own velocity, which

is compounded with that due to the excess of the repulsive over the attractive force, and in this way there is produced that curved outline, shaped like a parabola or a hyperbola, which is characteristic of the tails of comets.

We may sum up, therefore, by saying that the molecules of gas describe trajectories which first of all carry them towards the Sun and then take them away from it, with the result that the actual shape of the whole is that of a hollow cone in which the comparatively thin walls are formed of moving particles.

The amount of curvature backwards from the radius vector depends, in Bredichin's opinion, upon the value of the pressure of radiation, and this value varies with the nature of the ejected gases. An almost straight tail is an indication that hydrogen is being emitted ; one that is slightly curved, like the principal tail of Donati's comet, would be composed largely of hydrocarbons ; while a short tail, with backward curvature very much pronounced, would be associated with metallic vapours of high density, sodium, magnesium, etc.¹

Some comets show all three types at once, and indeed it may be said that every case exhibits the most disconcerting singularities. It seems impossible to adopt any system of classification. At one time a comet makes its appearance with six tails spread out fanwise through an angle as great as 60 degrees, as happened when Cheseaux's comet appeared in 1744 ; at another, the tail makes an angle of some 20 degrees with the radius vector, or is even transformed into feathery plumes on the side nearer the Sun ; or again, as in the case of Morehouse's comet of 1908, we witness pulsations of light travelling along the tail from one end to the other in the space of a few seconds, which seem to be connected with violent perturbations interrupting the discharge of the materials that are repelled backwards.

In short, if the appearance of a comet may increase the evidence for some theory, it is just as likely to raise a host

¹ See "Ann. de l'Observ. de Moscou," t. vii, pt. I, p. 60.

of unsolved problems ; and it is not too much to assert that we are almost completely ignorant of the laws which govern this mysterious class of bodies.

The terror which these stars used to cause has to some extent disappeared, but this is only because astronomers have so often affirmed that a collision with one of them would be quite a harmless occurrence. Yet what do we really know about it ? If the nucleus of a comet is composed of an enormous agglomeration of blocks of rock or metal, of all sizes, we should be wise not to wish for such an experience as would settle the question. In any case, it is exceedingly likely that if a comet were to fall on a town like Paris it would do more damage than a raid of German gothas, and scarcely a stone in the beautiful city would be left standing.

We need not smile too confidently, therefore, at the narrations of chroniclers when they tell us how people in mediaeval times were filled with alarm and panic by the appearance of those beautiful comets which seem since then to have left us unvisited. On the whole, it seems to me that the astronomers of those far-off times probably arrived, by mere intuition, nearer the truth than their successors in the eighteenth century, who denied the existence of "stones fallen from the sky," and professed to share the ideas of Babinet who spoke of comets as "visible nothings" while, all the time, in spite of their comparatively small mass, they probably weighed several million tons.

It is true, however, that more often than not, the terrors inspired by comets have been exaggerated ; and that naturally brings me to speak of the famous legend to which the appearance of Halley's comet in 1456 gave rise.

Laplace alluded to it in his *Exposition du système du Monde*, where he wrote about the comet as follows : "The long tail which it drew behind it spread terror throughout Europe, where already consternation was rife at the rapid success of the Turks, who had just overthrown the Greek Empire ; and Pope Calixtus ordered that

public prayers should be offered, in which *the comet* and the Turks *should be exorcised*.”¹

Such is the story which has been embellished during the last century in popular works. Laplace's words have been copied and rearranged and paraphrased, without a suspicion of any documentary justification.

The first offender was Arago who, in a Note in the *Annuaire du Bureau des Longitudes* for 1832, did not hesitate to write as follows : “ So great was the alarm of Pope Calixtus III. that he ordered that for a certain time public prayers should be offered each day at noon, in which *the comet and the Turks should be excommunicated at one and the same time* ; and in order that nobody should fail in performing this duty, he established the custom, which has ever since been observed, of the ringing of church bells at mid-day.”²

Thus, while Laplace had used the word *exorcise*, Arago speaks of the comet's being excommunicated. Yet he is not entirely consistent on the point, for in his *Astronomie populaire* he returns to Laplace's less precise term, and writes, “ They exorcised the comet and the Turks at the same time.”³ But as Fr. Thirion⁴ has picturesquely put it, the word “ excommunicate ” has now been set going, and will make its way.

Babinet, in 1855, shows us Calixtus “ hurling at the comet a timid anathema.”⁵ Why *timid* ? Further on, in another passage, he alludes to “ the exorcism and the anathema hurled at it by the Pope.”⁶

¹ LAPLACE : *Exposition du système du Monde*, l. iv, ch. iv, p. 283 (1829 edition).

² “ *Annuaire* ” for 1832, p. 244. It may be assumed that Arago wrote in good faith, for on the same page he expresses the hope that the reigning pope will not renew the *brief* of his predecessor on account of the comet of 1832. He must therefore have believed in this *brief*, although it in fact never existed.

³ ARAGO : *Astr. pop.*, t. II, p. 464. See also p. 368, where he says, “ The saying of the Angelus which was enjoined by Pope Calixtus, in which the comet and the Turks were exorcised together, was certainly not the kind of thing to calm the minds of nervous people.”

⁴ J. THIRION : *La Comète de Halley*, in “ *Revue des Questions scientifiques*,” October 1909, p. 681.

⁵ BABINET : *Études et Lectures*, 1855, vol. I, p. 34.

⁶ *Ibid.*, pp. 126-127.

Flammarion, in his *Astronomie populaire*, treats the matter with greater freedom. He rearranges the statements of Arago and Babinet, and tells us of Calixtus III. inviting "the faithful to say a prayer in order to exorcise the comet and the Turks."¹ And two lines farther on, he commits another historical blunder when he says, "It is from this that the Angelus dates."² Yet a little simple research would have taught him that the Angelus had been instituted 361 years earlier in 1095 by Pope Urban II. at the Council of Clermont; and 140 years before the appearance of the comet in 1456 Pope John XXII. was urging this prayer afresh on the whole of Christendom.³

When history is written like a romance, without any references, it is liable to contain errors of this kind. So we have numerous later authors writing in the same strain—Draper,⁴ Guillemin,⁵ and many others; but the climax is reached by Robert Grant who, speaking of Calixtus (whom he calls Calixtus II.) says, "He also issued a bull, in which he *anathematized* both the Turks *and the comet*."⁶

From these last words one might suppose that a bull of Calixtus III. exists in which the comet is at the very least mentioned, but there is nothing of the sort in the *Bullarium romanum*, or in the *Letters* of Calixtus which were published two centuries ago.

As long ago as 1858 Faye, who had studied the question, stated that he had not found a single word about the comet in the official documents which he had consulted,⁷ and in the year 1882 he returned to the subject and repeated his former assertions, defying anyone to disprove them.⁸ No one has taken up his challenge, yet living authors continue

¹ FLAMMARION: *Astr. pop.*, p. 599 (1880 edition).

² *Op. cit.*, p. 599.

³ TH. MOREUX: *Les Comètes*, in No. 283 of "Conférences," p. 27. Paris, B. Presse.

⁴ DRAPER: *Les conflits de la Science et de la Religion*, p. 194. Paris, 1875.

⁵ GUILLEMIN: *Les comètes*, p. 21.

⁶ R. GRANT: *History of physical Astronomy*, p. 305. London, 1852.

⁷ See "Cosmos," 1858, t. XIII, p. 647.

⁸ See "Revue scientifique" for March 11, 1882: *La Figure des Comètes*, a lecture by H. FAYE.

as in the past to relate that a pope once conjured, exorcised or anathematised a comet.

It is interesting to see how such a story originated, and contemporary writers have not been backward in investigating the matter. Their researches have tended to show that Laplace must have copied Bruys or Fleury,¹ who had commented on a passage in the writings of Platina in which the author, a contemporary of Calixtus III., speaks in one long sentence of the appearance of Halley's comet and the prayers which the Pope enjoined on behalf of the armies which were fighting against the Turks.² Mention is made of these prayers, as well as of the midday Angelus, in the bull dated June 29, 1456, at which time the comet was shining with great brilliance, but in this again there is nowhere any reference to the terrifying object.

In spite of this incontrovertible evidence, writers will still be found, no doubt, who would rather falsify history than give up the legend.

One other fact may be mentioned to show how carelessly Arago accepted the most ridiculous stories without any attempt at verification. Writing in his *Astronomie populaire* about the plague which was raging at the time of the appearance of the comet of 590, he says, "When the sickness was at its height, a sneeze was often followed by death; and hence arose the custom which still exists of greeting a sneeze with a 'God bless you!'"³ Once again it is a gross misstatement; and if Arago had consulted some author of literary attainments he would have learnt that the custom dates back to a far earlier period, since it is referred to in the writings of Pliny.⁴

¹ BRUYS: *Histoire des papes*, 1732-34, La Haye. FLEURY: *Histoire ecclésiastique*, t. XV, p. 402 (1777 edition). See also CALVISIUS who in his *Opus chronologicum* (1606) copies Platina (with embellishments).

² PLATINA: *Vita Calixti III.*, p. 283.

³ ARAGO: *Astr. pop.*, t. II, p. 464.

⁴ PLINY, II, ch. II, § II. Cf. C. CANTU: *Histoire des Italiens*, t. V, p. 162, note.

CHAPTER XII

SHOOTING STARS AND METEORITES

ON the 27th of February, 1826, a major in the Austrian army named Biela discovered at Johannesburg a comet which now bears his name. Ten days later the same star was seen by Gambart at Marseille, and the French astronomer, when he had calculated the elements of its path, at once noticed their resemblance to those of a comet which had been observed in 1805 as well as in 1772, and of which the period was six years and three-quarters.

The calculations were made again by Damoiseau, who based them on the observations, and he soon announced that Biela's comet would return on November 27, 1832,—which it did punctually to the very day. In 1839 it was not possible to observe it on account of unfavourable conditions. But it returned in 1846, and now its physical aspect was changed. A kind of protuberance was to be seen to the north of the nucleus; about a month later (on January 15) two separate nuclei could be distinguished; then a dozen more days passed, and the two stars were 200,000 miles apart, each furnished with a separate appendage.

After this, their return in 1852 was awaited with some impatience. At the right time the two comets re-appeared, but the distance separating them was by now increased to more than 1,200,000 miles. In 1859 and 1866 they were watched for in vain, and the question began to be asked whether their return in the month of November 1872 could be expected. The month arrived, and there was no comet; but just as the observers were thinking about adding its name to the list of stars which had disappeared,

suddenly on November 27 a shower of shooting stars fell upon the terrestrial globe. In a space of six hours more than 30,000 meteors could be counted, and when the tempest was at its height they were seen at the rate of 400 per minute. The fact was that we had passed through the comet, or rather through a piece of it.

The lesson was not thrown away, and a few years later Schiaparelli proved that several swarms of shooting stars must have originated in a similar way. If we consider a mass composed of minute fragments—an almost spherical cloud of cosmic dust, the elements of which are held together by their mutual attractions—it is easy to show by the principles of celestial mechanics that the effect of the Sun's action upon the whole cloud will be to lengthen it out and gradually to disperse its constituent parts, until at last all the tiny fragments are spread out along the original orbit and follow one another in more or less regular succession. In this way we have an explanation not only of the streams of meteors derived from comets which have now disappeared, but also of the swarms associated with comets which still exist.

The theory holds well enough, and accounts for the most important features which have been observed. Thus the meteors belonging to the same swarm are animated by the same velocity, which is in general the velocity of the comet; and they seem to diverge from the same region in the heavens, an area more or less extended which is called the *radiant point*. It is evident that if the particles whose path we cross are moving along parallel trajectories, they must appear to us as diverging from a centre in accordance with the same laws of perspective by which parallel railway lines are shown in a drawing as diverging from the "vanishing point."

It has been recognised since 1867 that the elements of the paths of several swarms were nearly identical with those of periodic comets which had been observed again and again. In this way the Leonids, a shower which bursts upon us in the middle of November, reveal their

SHOOTING STARS AND METEORITES 193

relationship with Tempel's comet (1866, I.) ; the Andromedes of November 20, with the famous comet of Biela which has disappeared ; the Perseids of the middle of August, with the comet 1862, III., which is known as Tuttle's. All these swarms are designated nowadays by the constellation which contains their radiant point at the present time and from which therefore they seem to come ; and it has been found possible to associate a large number of them with periodic comets, for example the Lyraids of April 21, the Aquarids of May 4, the Draconids of June 28, and so on.¹

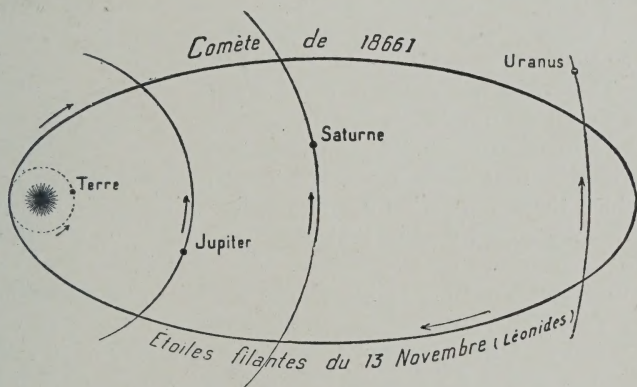


FIG. 49.—ORBIT OF THE COMET 1866, I., SHOWING ITS RELATION WITH THE SWARM OF THE LEONIDS

Interesting, however, as this theory is, it would seem that it is by no means completely confirmed by the facts. For example, the swarm of the Perseids, which we associate with Tuttle's comet of 1862, existed long before the comet was discovered ; mediaeval chroniclers knew it under the picturesque name of the "Tears of Saint Lawrence." It may be that the orbit of the meteors is the same as that of Tuttle's comet, which has a period of 123 years, and that

¹ See F. DE ROY : *Les étoiles filantes et les comètes*, in the "Revue du ciel" for December 1919, p. 738.

along this orbit there move certain more closely condensed swarms following one another, as has been supposed, at intervals of 33 years. But also it might quite well be the case that we are here dealing with different comets following nearly the same paths, in other words with a *group* of the kind to which reference was made in the last chapter.

On all sides observations are becoming more numerous, and in consequence our catalogues are continually being enriched with so many new periodic comets and swarms that the chance of our establishing identifications between the two classes of meteors becomes greater every day ; and probably the time is not far distant when we shall find scarcely any difficulty in associating every swarm with the elements of a comet that is already known.

The criticisms which have here been made on matters of detail do not touch the theory which seeks to explain the formation of shooting stars. It becomes more and more probable that they are really derived from stars upon which the Sun's action has had a dissolving effect. Some one may object that in that case there ought by this time to be no more comets left in existence ; in view of the millenniums of time during which they have been compelled to pass and repass close by the glowing furnace of our central Sun, every one of them has had plenty of time to disappear and be dispersed in dust. Such an objection is quite fair and to the point, but two remarks may be made. First, it certainly seems to be a proved fact that the best known periodic comets tend to diminish in brightness, considerable portions of material being lost by means of the tail,¹ and the principal mass shedding parts of itself on its journey as happened in the case of Biela's comet. Secondly, it may be questioned whether we have any certainty that these fragments do not in the long run re-form themselves into new comets, especially when they are near aphelion and consequently less influenced by the Sun's action.

It is in the light of these considerations that we must

¹ This seems to be the case with Halley's comet.

approach the interesting problem of meteorites. Some writers have wished to see in them the relics of a lost planet ; others have regarded them as bombs hurled forth during the eruptions of lunar volcanoes, or even projected from volcanoes on our own globe or those on distant planets and their satellites. The reasons alleged for these views have always seemed to me puerile. Quite recently, for instance, M. Belot admitted the conclusion of M. Stanislas Meunier that in no case do meteorites exhibit any signs of fusion ; but that did not disturb him, for he was ready to postulate a special kind of volcanic activity to suit the case.¹ Solutions of this kind, with their special contrivances, are not going to satisfy anyone ; they are fantasies of the imagination which, to say the least, fail to appreciate those great laws of cosmic evolution by which all things are bound together in a wonderful harmony.

Just as there exists no sharply defined line of demarcation between the planets and the asteroids, or between the latter and the short-period comets, so there is no specific difference to be perceived between the constituent parts of a comet and meteorites.

The main objection to this theory, or rather the difficulty involved in it, may be stated in a few words : how, in that case, are we to imagine the mode of agglomeration of meteors, having regard to the fact that in some instances they exhibit a high density ? We might reply by admitting the possibility of exceptional cases ; merely because our theories do not explain everything, we are not bound to conclude that they must needs be false. A truer logic suggests a different alternative : it may be, in fact, only that the theories are at present incomplete.

Are there, then, any incontrovertible facts which justify our assertion that a relationship exists between comets, shooting stars, and meteorites ? From the mechanical point of view, there is no difficulty about supposing that these different classes of meteors are identical in their

¹ E. BELOT : *Le volcanisme expérimental*, in "Revue scientifique," November 15 and 22, 1919.

origin. Cases have been quoted of meteorites accompanying swarms of shooting stars ¹; on the other hand, some of their velocities have been calculated to be hyperbolic,² but just the same used to be said about the comets themselves, and we have seen that the hyperbolic path may result from a combination of planetary and solar attractions. In my opinion, therefore, it is to chemistry that we must ultimately appeal for a settlement of the question.

We know 275 well-authenticated meteorites, and they have all been subjected to analysis. When they are heated, the lightest gases are the first to be given off,

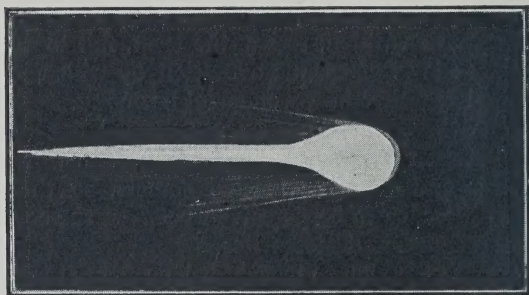


FIG. 50.—METEORITE OBSERVED AT BOURGES, WITH ITS BRIGHT TRAIL
(From a drawing by the Abbé Th. MOREUX)

and these are found to be the very ones whose presence has been detected in the nuclei of comets—hydrogen, helium, nitrogen, carbon, sodium, magnesium; even iron has been discovered in some cases. Much the same may be said also about shooting stars, for in their case the spectroscope has revealed the presence of sodium, magnesium, and complex carbon compounds.

It has been asserted that high pressures would be required to explain certain phenomena of transformation for which

¹ See Miss CLERKE : *History of Astronomy*, p. 340.

² See an article by Fr. CARBONNELLE, in "Revue des Questions scientifiques," for January 1889; also TISSERAND : "Bull. Astr.," t. VIII, p. 460.

M. Stanislas Meunier holds that there is evidence, and to account for the presence of minute diamonds and of graphite—perhaps even of coal, for that too has been mentioned. Yet what do we really know as to the origin of carbon? While almost all investigators, working on the lines of Moissan's experiments, have supposed that enormous pressures were necessary for the solidification of carbon and the production of the diamond, we have recently (1908) seen M. E. de Boismenu achieving this famous synthesis by the help of carbon compounds and the electric

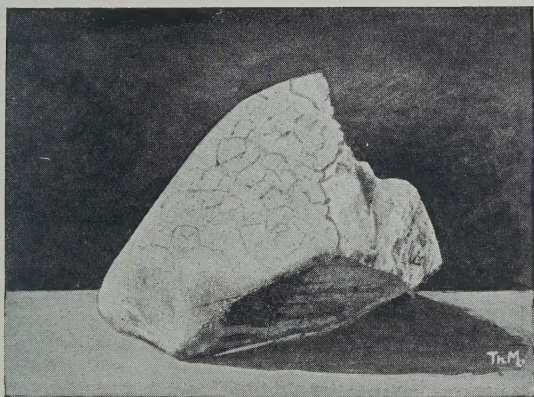


FIG. 51.—THE "ALLEGAN METEORITE," WHICH WEIGHS 66 LBS.

furnace, without having recourse to any exceptional pressure.¹

With regard to transformation, it would be well for the reader to refer to what one of the most eminent geologists, M. P. Termier, has recently written on the subject, showing that he regards it as one of the unsolved problems of geology.² And as to coal, it is to be noted that M. Lenicque

¹ See E. DE BOISMENU: *Fabrication synthétique du diamant*. Paris, B. Tignol.

² P. TERMIER: *Les grandes énigmes de la Géologie*, in "Revue des Questions scientifiques," January 1920, p. 68.

regards it as a solid carbon compound of mineral origin as much as petroleum.¹

The mode of the formation of meteorites is not really a more troublesome problem than the origin of grains of oolitic iron pyrites, or schists, or beds of coal, or folds in the Earth's surface strata, or the evolution of radioactive substances,—or indeed than the explanation of any of the different forms of matter which in the course of ages have been evolved either in the heart of the Earth or on its surface.²

Sir Norman Lockyer, one of the greatest scientists of this generation, long maintained that the world is formed entirely of meteorites ; ³ and although his hypothesis is open to objection in matters of detail, at least it rounds off the whole Universe in a comprehensive theory. The zodiacal light, Saturn's rings, comets and meteors, planets and suns—all these would but represent different stages in one grand process of evolution which began with the nebulae.

A theory like this may be untrue or incomplete, and this the future must decide. Meanwhile it is much to be preferred to the barren notions of those investigators who divide up the Universe into watertight compartments, and are content to approach the study of nature's mighty phenomena as if they only needed to be examined through a microscope.

¹ F. LENICQUE, in "Revue du ciel," April 1920.

² Th. MOREUX : *Origine et évolution des météores*, in "Revue du ciel," December 1919 ; see also S. ARRHÉNIUS : *L'Évolution des mondes*.

³ Sir N. LOCKYER : *Meteoritic hypothesis*.

CHAPTER XIII

THE STARS

“**W**HAT I know best is how I began.” This remark might well be made by an astronomer as he leaves the study of the solar system to enter upon the wider investigation which awaits him. Our Sun is really no more than a single star in the midst of the host of celestial bodies, and the field which now opens out before our gaze might almost be called infinite in extent. Whereas observers in the past registered only about 5,000 stars which were visible to the naked eye, a telescope of 5.4 inches aperture makes it possible for us to see seven millions. All these are classified according to their brightness as reckoned on an agreed scale, or, as astronomers say, according to their *magnitude*; and in this classification a fairly constant rate of increase in the numbers has been noted: as a general rule, the number of stars of one magnitude is three and a half times greater than that for the next brighter magnitude. Now at the present time instruments like the Mount Wilson telescope, which has an object-glass of 100 inches, easily bring within our vision stars of the eighteenth magnitude; consequently, if the rate of increase were maintained, we ought to arrive at a total of 1,400 millions of stars, and even this number would be far exceeded in the case of photographic records which show those of the twenty-first. But actually this is not the case, for the law seems to fail after the thirteenth magnitude is reached, and 1,000 millions is the maximum number of stars that we can claim on the most liberal estimate to have brought within the range of our perception.

Such were the conclusions of Astronomy only a short time ago; they all bore witness to a well-marked tendency

to regard *our* Universe, as we liked to call it, as comprehending within itself all existing matter. "If the system of stars," said Newcomb in his book on the Stars,¹ "extended out indefinitely, the whole heavens would be filled with a blaze of light as bright as the Sun"; while the fact is that the maximum light given by all the stars together does not exceed one six-millionth part of sunlight. But although these words are still true to-day, they cannot settle for us the crucial question, which may thus be stated: "Is it not possible that beyond the finite number of stars which make up our actual Universe, there are other worlds, other celestial objects, other systems—in a word, other Universes—immensely more remote than the farthest stars belonging to our Milky Way?" The astronomers of the last century were still answering this question with an emphatic negative, but those of our own time are not prepared to speak with the same decision, and everything leads us to conclude from our recent investigations that the boundaries of the celestial world must be considerably extended.²

This is the chief problem with which the whole science of Astronomy is concerned. If we are to understand what solutions are permissible, we must carry forward step by step our study of the stars which are scattered around us in such profusion; we must survey the ground, and try to dispose of a number of other questions with which the main problem is bound up.

The first of these has to do with stellar distances. We have already seen how, by methods of great ingenuity, we have succeeded in calculating the dimensions of the solar system. Our investigations were based upon a knowledge of the Sun's parallax; but when we apply this word "parallax" to the stars, we must define it quite differently. They are so far off that the Earth's radius, as seen from one of them, is no longer large enough to be measured; for a star, indeed, our poor little world cannot be said to exist,

¹ S. NEWCOMB: *The Stars*, p. 230. London, J. Murray.

² See especially the work of Shapley, which will be considered in the following chapters.

nor can the larger world of Saturn or even of Jupiter ; all these planets are lost in the light of the Sun, upon which alone devolves the task of representing us among the other members of the great celestial army.

In order, therefore, to calculate the enormous distances which separate us from the stars, astronomers have found themselves compelled to choose a base-line more suitable for comparison with the lengths which they want to determine, and for this they have taken the astronomical unit of length, or the distance between the Sun and the

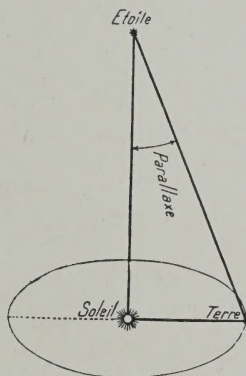


FIG. 52.—THE IDEA OF PARALLAX AS APPLIED TO THE STARS

Earth—that is to say, one-half of the major axis of the orbit which we describe in the course of a year. Hence follows a definition which must be continually kept in mind : the parallax of a star is the angular measurement, for an observer situated upon it, of the mean radius of the Earth's orbit.

This angle we may have some hope of detecting, thanks to our own displacement in space. If we observe very exactly the position of a star in the heavens, on two occasions separated by an interval of six months—that is to say, when we know that we are at the two extremities of a diameter of our orbit—then through the effect of perspective the star will be projected on two different

points of the celestial sphere, and we can in this way deduce its double parallax.

All this is quite correct in theory, but the difficulty begins as soon as we come to practical application. We have learned from experiments that in no case does this parallax amount to as much as one second of arc, in which case the star would still be 206,265 times farther off than the Sun. It can easily be understood therefore what difficulties have had to be overcome in order that star-distances may be measured.

Until the last few years, the record for the shortest distance was held by the star Alpha Centauri, which is visible in the southern hemisphere and has a parallax of $0.76''$; this would give for its actual distance nearly 25 billions of miles. As light travels at the rate of about 186,000 miles per second, it would take no less than 4 years and 3 months to reach us from this neighbour of ours. In 1916, however, Mr. Innes of the Johannesburg Observatory found a star which was slightly nearer; strange to say, this new discovery, a star of the eleventh magnitude, is in the same constellation as the other, and Mr. Innes has assigned to it the name *Proxima* Centauri. Its parallax is $0.78''$, according to which its distance from us is some 23 billions of miles, or about 4 light-years. This star, then, is actually our closest neighbour in the heavens, and from this we can judge what enormous distances must separate those bright points which are dotted in thousands all over our star-photographs.

It used to be thought that the faintness of a star's light was proportioned to its distance, and no doubt this law holds good if we are dealing with a large number of cases, but in so far as any particular star is concerned it is more often than not inapplicable. For instance, we find that Sirius, the most beautiful star in the whole sky, is twice as far away from us as Proxima Centauri; Vega's distance is 25 light-years, Capella's is about 41, and the Pole Star's is 47.

Unfortunately this exact geometrical method of apparent

displacements ceases to be of any help to us as soon as the distances become very great, so that very few parallaxes can be measured by its means with any certainty. When it comes to measuring a few hundredths of a second, the errors of observation very often reach 100 per cent., and we cannot be too cautious about accepting the results unless they have been checked over and over again. But during the last few years, astronomers have discovered new methods for evaluating distances, and we shall see in the next chapter to what extent the figures thus obtained can be trusted.

There is another cause of error to be reckoned with in the calculation of stellar distances, besides the smallness of the angles involved, namely that which arises from the *proper motions* of the stars. Those people who long ago distinguished the stars from the planets by calling the former "fixed" made a serious mistake. Of course their respective positions change only very slightly in the course of several centuries, but the displacements are not on that account to be ignored.

The movements appear to be small because the stars are so far away, but in reality their absolute values are considerable. One's first idea might be that the nearest stars would possess the greatest proper motions, but this is not the case; their velocities seem to be determined by quite a different law, and to be dependent rather upon the chemical constitution of the bodies themselves. Out of the thirty stars known to be changing their position most rapidly, more than half are invisible to the naked eye, eleven are fainter than the eighth magnitude, and only two are very bright.

It must be remembered, further, that in dealing with the statistics of these motions, careful account must be taken not only of the rate of apparent displacement upon the celestial sphere, but also of the movement in the direct line of sight. The two have to be compounded with one another, and it is the resultant of the two velocities which actually gives us the proper motion.

As regards the first (or *tangential*) displacement, this cannot be evaluated in miles unless we know the star's distance from us. When measured in terms of arc, it is generally very small, amounting to only a few seconds. The greatest value is attained in the case of a quite small star which was discovered by the Dutch astronomer Kapteyn in the southern hemisphere in 1897; it moves through nearly 9 seconds of arc in the course of a year, which means that in about two centuries its position in the sky is shifted through a distance equal to the apparent diameter of the Moon's disc.

The other kind of displacement, taking place along the line of sight, is called *radial*. The absolute value, in miles per second, of the velocity in this case can be obtained spectroscopically, in accordance with the Doppler-Fizeau principle to which we have already referred. Just as the sound emitted by the whistle of a locomotive is raised in pitch while the engine approaches, and is lowered while it is receding, so the lines of the spectrum, as Doppler remarked in 1842, must be shifted somewhat towards the violet or towards the red end according as the source of light is moving rapidly towards or away from us. This principle was applied by Fizeau in 1848 to the investigation of radial velocities, and it has proved inexhaustible as a means of obtaining information. By its means we are enabled to measure the rate of displacement of all the stars relatively to our Sun, even in those cases in which they seem to us to be stationary as regards their position on the celestial sphere.

The result of all the measurements that have been made is to show that the stars possess a proper motion of about 20 miles a second; but this is only an average value, and many stars are known to us for which the velocity is much greater. Alpha Gruis, for example, has a velocity exceeding 40 miles per second; our neighbour 61 Cygni, which is only eleven light-years away from us and comes fifth in the order of distances, is nineteenth in the order of proper motions, with a velocity of 51 miles per second.

But all records are beaten by Arcturus, in Boötes, which rushes along at the rate of 257 miles per second—a speed which would take it from the Earth to the Sun in four days.

Other stars that may be specially mentioned are 15290 Lalande with a velocity of 206 miles per second, 1830 Groombridge with 159 miles per second, and Mu Cassiopeiae with 103 miles per second.

These stars, hurtling through space like mighty projectiles, raise most troublesome problems for the astronomer. To what do they owe their tremendous velocities?

Lord Kelvin has calculated the amount of gravitational matter which would be necessary to produce the motions observed in general among the stars, and has found that there would have to be at least a thousand million suns like our own, distributed at random throughout a sphere of radius 3,262 light-years.

Since the number of stars is so great, and at least a third of the velocities which it has been found possible to express in miles per second exceed the maximum theoretical velocity of 25 miles per second which was calculated by Newcomb, it is difficult to think that these rapidly moving stars are merely wanderers which have encountered our system by accident. Whether they have always belonged to it is of small importance; what is certain is that they are now by no means a negligible part of it, and that we must take account of them if we wish to make a thorough study of the mechanism of the sidereal world.

The application of the Doppler-Fizeau principle has led by a similar line of reasoning to the solution of another problem which long disturbed the minds of astronomers. Since all the stars, it was argued, have a proper motion, our Sun, which is itself a star, cannot be at rest; and we may reasonably seek to determine the elements of its movement in space—its direction, namely, and its velocity. The problem was first taken up by Sir William Herschel, and nothing but the genius of that prince among observers

could have produced at the time even an outline of a solution.¹

If the Sun were in motion by itself, and all the other stars were at rest, it would be easy to interpret the results of our observations in regard to the displacements of the latter ; but the complexity of the question arises precisely from the fact that the stars are all in motion, and that their movements are in different directions. At the same time, there can be no doubt that if the Sun is moving forward in a definite direction, the whole system of stars will tend, by the laws of perspective, to move away from that spot in the heavens towards which our central luminary is carrying us. To this mathematical point which we want to discover, the name solar *apex* has been given. Exactly the contrary effect will be produced on the diametrically opposite side, and the stars will all show a tendency to approach the *antiapex*.

In Herschel's time, very few proper motions were known with sufficient accuracy to justify the hope that a rigorous solution of the problem was possible. However, the Hanoverian astronomer, from a consideration of the proper motions of seven very bright stars, thought he could infer that our Sun was bearing us along towards a point in the constellation Hercules ; and such is the fascination which distinguished scientists always exercise over men's minds that, although more recent and more trustworthy determinations have been made, Sir W. Herschel's results still figure in many popular Astronomies, as well as in most textbooks on the structure of our universe.

But the work that was done on this difficult problem in 1783 can no longer content us, and our conclusions may now be based not upon an insignificant number of stars but upon the thousands to which it has been found possible to apply spectroscopic examination. Further, their distances and tangential displacements matter little in this inquiry ; when we have roughly determined the direction in which

¹ See Th. MOREUX : *Où nous entraîne notre soleil ?* in "Scientia," 1913, xxxi, 5.

the Sun is moving, it is sufficient to compare the mean radial velocity of the stars situated in that neighbourhood with that of the stars which we are leaving behind us. Among the former, movements of approach ought to predominate ; among the latter, movements of recession ; and then one-half of the mean difference represents the velocity with which our solar system is being borne along relatively to the stars with which the comparison has been made.

The results recently obtained are certainly curious, for they show that different velocities are deduced, and different determinations of the apex, according as the examination is restricted to stars of some particular type, that is to say, to those which have the same chemical composition. Hence it is necessary to combine the results for different types of stars, and this has been done by several astronomers, especially Newcomb, Kapteyn, and Stroobant.

The best as well as the most recent investigation seems to be that of Professor Boss, who has taken into consideration the proper motions of more than 5,000 stars, distributed uniformly over the whole sky.¹ According to him, our Sun is taking us towards a point situated in the constellation Lyra, a little to the south of Vega. Our proper motion would seem to be between 12 and 15 miles per second, and the lower value seems to me the more likely. The length of the journey that we make each year in the company of the Sun is equal to about twice the diameter of the terrestrial orbit.

Relatively, no doubt, this is not much, since light would take only 35 minutes to go the same distance ; still our movement is twenty times quicker than the muzzle-velocity of a shell discharged from a gun. So great, however, are celestial distances that, in order to arrive in the neighbourhood of Vega, assumed to remain stationary, we should have to complete a long journey lasting nearly 350,000 years ! If we compare ourselves with the brilliant

¹ See S. NEWCOMB : *The Stars*, p. 89.

express in Boötes which flies along at the rate of 257 miles per second, while we move with less than the average velocity of the stars, we shall better understand Simon Newcomb's remark that "we were born in a very slow train."

Are we travelling in a straight line, or in a slightly curved path? We do not know. The answer to the question probably depends on another problem which is too complex for us to be able to deal with it at present—that of the distribution of the stars.

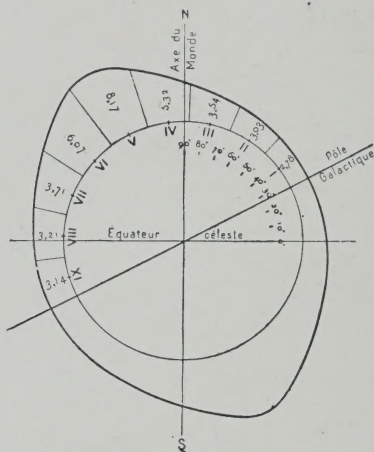


FIG. 53.—FIGURE TO SHOW THAT THE NUMBER OF STARS INCREASES AS WE APPROACH THE MILKY WAY

The merest glance at the vault of heaven on a clear winter's night will show us very plainly that the stars become more and more numerous as we approach the Milky Way. That large luminous band which completely encircles the sky is itself composed of an astonishing multitude of stars. Sir William Herschel, who first undertook to survey the heavens, was very quickly convinced that the stars were distributed in such a way that their numbers increased systematically towards the median

plane of the Milky Way. But again, as the "galactic" girdle divides the sky into two nearly equal portions, and really plays for us the part of an equator, we cannot doubt that our position is somewhere in the plane of this great cluster of stars. Thus we look out upon our Universe from a more or less central point of view, and if we assign to the whole the shape of a flat disc, or a double convex lens, all the appearances are explained; our line of vision does actually pass by fewer stars in the direction of the thickness of the lens than it does when directed along the diametral plane.

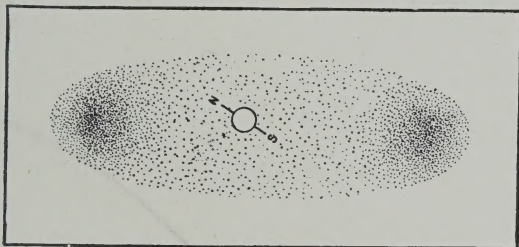


FIG. 54.—SECTION OF THE MILKY WAY, TO SHOW THE PROBABLE DISTRIBUTION OF STARS

Thus recent discussions have not upset the general views of Herschel, but at the same time they have left in our minds some doubt as to the distribution of the stars in the interior of the flattened disc to which we have compared the Milky Way as a whole.

It is quite true that apart altogether from the stars which are properly called galactic—that is to say, those which are faintest and most distant—the bright stars would still show on the whole a tendency to crowd together along the great circle of the celestial sphere which coincides with the plane of the Milky Way. The nearest stars, therefore, in Herschel's view, are distributed almost uniformly. But beyond these stars we must allow for the probable existence of a sort of stellar ring of con-

siderable density, reminding us of what we see in the annular nebula in Lyra.

The consideration of the distribution of matter in the

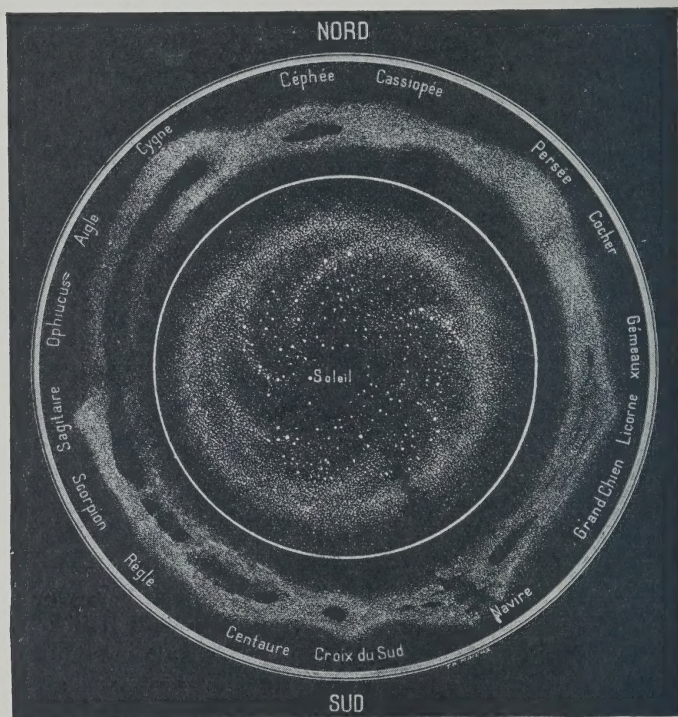


FIG. 55.—BETWEEN THE TWO CIRCLES IS A REPRESENTATION OF THE APPEARANCE OF THE MILKY WAY. WITHIN THE SMALLER CIRCLE IS A PLAN OF OUR UNIVERSE

(From a drawing by the Abbé Th. MOREUX)

central part of the whole system further suggests, according to Easton, the appearance of the spiral nebulae.¹ That the spiral curves are there, we may well believe, but

¹ Th. MOREUX : *Où sommes-nous ?* p. 81. Paris, B. Presse.

not in the way that Easton imagines ; the great mass of the ring would draw the curves towards itself, so that they would be divergent rather than convergent towards the centre. Each of these curves would be formed by an endless series of suns, and our own would have its place in one of the processions. I first published these views in 1911, in *Les Merveilles des Mondes*¹; they were suggested to me by a study of Gould's recent researches on the ring. Before that time I had supposed, with the majority of astronomers, that our Sun was a member of some star cluster. Gould,² Sulton,³ and Stratonoff⁴ tried one after another to determine the shape of this cluster, but in 1901 Kapteyn put an end to all such ideas. Apart from the well-defined globular clusters of which we shall speak later, the bright stars which are near to us exhibit no tendency to group themselves together ; indeed, as M. Stroobant has recently remarked, they seem rather to arrange themselves in streams having well-marked directions.

If we consider especially those stars whose movements relative to the Sun are small, we find that their apex is the same as ours. Already at the present time we know 18 stars possessing this characteristic, seven of which are brighter than magnitude 2.5 ; Alpha and Beta Persei, Alpha Cassiopeiae, Alpha Scorpii, Gamma Cygni, Epsilon and Alpha Pegasi, and our own Sun are all taking part in the same procession and moving towards the same goal.

Thus we have the condition of things which Miss Clerke once described so picturesquely : " It is," she said, " just as if we had chosen a compartment for our long journey through space." In this felicitous phrase she compares the series of suns in which we have our place to a long train, with its carriages all filled with travellers and following one another in interminable succession.

¹ TH. MOREUX : *Les Merveilles des Mondes*, p. 123.

² S. NEWCOMB : *The Stars*, p. 243.

³ See " Knowledge," July, 1891.

⁴ See " Bull. Soc. astr. de France," p. 357.

CHAPTER XIV

THE EVOLUTION OF STARS, AND STELLAR SYSTEMS

THE stars are so far off that the most powerful instruments are quite unable to give them any increase of size ; the small discs which they all seem to possess when seen through telescopes are due to diffraction, and experiment as well as theory shows that the size of the disc diminishes with the aperture of the instrument employed. It is not possible, therefore, to attempt a classification of the stars by means of any details which could actually be perceived. But this is made up for by spectrum analysis ; in passing through the spectroscope, carefully placed either in front of the object-glass or behind it, the ray of light which has come from the star is spread out over a long band and reveals to us the secrets of the star's inmost constitution.

Speaking generally, it may be said that the chemical composition of a star is connected with its colour. As long ago as 1867, Fr. Secchi had grasped the use that might be made of this fact, and working upon a large number of statistics had divided up the stars into several clearly defined classes : white or blue stars, like Sirius or Vega ; yellow stars, like our own Sun ; red or orange-coloured stars, like Antares in Scorpio ; and faint ruby stars like 19 Piscium.¹

As the technical resources of science have advanced, however, it has been found necessary to add intermediate classes to those first suggested. So, too, it seems clear

¹ One of the most recent, as well as the most curious, results of spectrum analysis has been to show that the velocities of the stars are greater in proportion as the rays near the red end of the spectrum enter more markedly into the composition of their light.

that Secchi's first class, which includes half the stars and is composed of youthful suns surrounded by a thick atmosphere, does not represent the earliest stage in condensation. Numbers of stars serve as links between it and the nebulae; some of them show the lines of helium and hydrogen—those light gases whose presence indicates chemical youth; while others appear to be in a still less advanced state, and have affinities with certain nebular types.¹

A new science, that of stellar spectroscopy, has thus come gradually into existence, and its boundaries are being continually widened. Some observatories like that at Harvard are devoting themselves almost exclusively to the task of cataloguing and classifying the stars according to their nature. As a result, there can no longer be any doubt that the birth, development and death of stellar worlds all take place as part of a process of inorganic evolution; the elements are being transformed before our eyes, and a belief in the transmutation of matter is irresistibly forced upon the mind of the astronomer.

At this point another question arises. We know how the stars gradually grow old, and pass through the whole scale of decreasing temperatures. But what stages do they go through *before* reaching their maximum temperature? Evidently, from the thermal point of view, through the inverse series. From this it follows that we ought to find in the heavens stars which are at the same temperature, but of which some are on the descending, others on the ascending scale. And for these the chemical composition must differ—a fact which has led to the construction of a new theory and a new method of classification due to Sir Norman Lockyer. They are based upon the lines which are *enhanced* by the electric spark—lines which are supposed to correspond to a disintegration of various simple substances into proto-elements.²

¹ For the different systems of classification which have been adopted, the reader may refer to a note on the subject by M. DE GRAMMONT in "Ann. du Bur. des Long.," 1913, p. 297.

² See Sir N. LOCKYER: *Inorganic Evolution*.

The attempt has since been made, either by this method or by similar ones, to determine the absolute temperatures of the different stars, but it is scarcely necessary to say that in no case are the results to be taken seriously. Just as the temperature of a body cannot be lower than 273 degrees below zero, so it may well be that the thermometric scale has an upper limit also, and a temperature of tens of thousands of degrees may be only a figment of the imagination.

It was stated in the last chapter that we are now in possession of other methods for measuring the distances of the stars, besides the one based on geometry. A remarkable example of this is furnished by spectrum analysis.

The apparent brightness of a star depends partly on its real or intrinsic brightness and partly on its distance. Suppose that there are two stars, of the same apparent brightness; then it is clear that if we knew their real brightness we could infer their relative distances, so that, for example, if the intrinsic brightness of the one were nine times greater than that of the other, it would be three times as far away. Now each spectral type possesses its own special characteristics, and so it is sufficient to measure the relative intensity of certain rays to arrive at a determination of the real brightness—or, if the term is preferred, the absolute magnitude. As the apparent brightness can always be measured with great precision, we are thus provided with a means of obtaining the distance of a star in terms of that of another star of the same kind whose parallax is already known.

This method, which is due to Mr. Walter S. Adams, has been employed at Mount Wilson, side by side with the ordinary methods, and it has never been found to fail. "It has been applied to more than a thousand stars," Mr. Adams has written, "and the accuracy of its results seems to be of the same order as that of the results obtained by direct measurement. It has the advantage of being applicable to stars of very small parallax, and it is probably

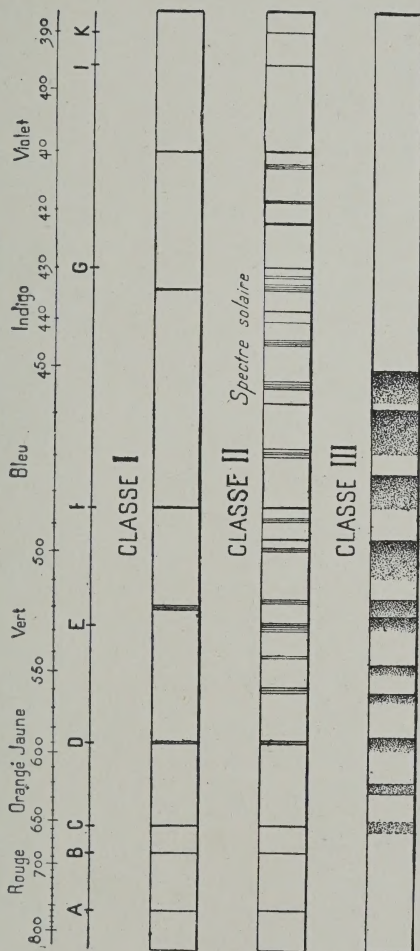


FIG. 56.—CLASSIFICATION OF THE STARS ACCORDING TO THEIR SPECTRA; AT THE TOP IS SHOWN THE SOLAR SPECTRUM WITH THE WAVE LENGTHS IN MILLIONTHS OF A MILLIMETRE

in such cases that its employment will be of most service." ¹

These considerations, and certain others based upon interferometric methods, have even enabled us to form an idea of the mass and volume of some of the stars. The little star 21185 Lalande, which is one of our nearest neighbours, is scarcely larger than Jupiter; while another near star, 243 Z. V. Cordova, is even smaller. But side by side with these Lilliputian systems gigantic ones are being evolved in comparison with which our Sun seems a mere pygmy.

Sirius is an enormous glowing sphere twelve times bigger than our luminary; Procyon in Canis Minor is still larger, being the equivalent of sixteen suns like ours. And if, with the swiftness of thought, we could pay flying visits to some others among the brightest stars—Deneb in Cygnus, the second star of Ursa Major, Vega the beautiful blue star in Lyra towards which we are being borne along, Pollux in Gemini—we should always find ourselves confronted by enormous blazing masses, dotted about like gigantic beacons amid the blackness of the sidereal night, beside which our Sun would be about as effective as the lamp on a floating buoy compared with a modern lighthouse.

But look at Arcturus, 138 light-years away. What a spectacle it presents! If this brilliant star in Boötes were placed instead in the position occupied by the Sun at the centre of our system, it would be 13,300 times larger, and would fill more than a third of the orbit of Mercury. But figures greater than these can be given. Imagine a sphere whose radius exceeds by 14 million miles the distance from the Sun to the Earth, the mean value of which is nearly 93 million miles; fill this immense region with incandescent material; and you will then have some notion of the size of Betelgeuse, the beautiful star in Orion, which is as large as 15 millions of our Suns thrown into one.

When astronomers first calculated these results, they

¹ See W. S. ADAMS: *Détermination spectroscopique des distances stellaires*, in "Revue du ciel," October 1918.

must have stood aghast with amazement, but still there were more surprises to follow. Aldebaran, the eye of Taurus, is an enormous globe of such vast dimensions that if it were placed at the centre of our system, the planet Mars would revolve entirely inside it, although at a distance from the centre of 142 million miles. Aldebaran is equal to 30 millions of suns like ours, but Antares in Scorpio is actually five times larger, being equal to 150 millions. Such figures are far beyond the power of our imagination to grasp.

If we know very approximately the masses of these celestial giants, we can form a very good estimate of their density. Here the results are even more startling, and raise fresh problems for our consideration.

A cubic decimetre of the Sun's substance, of average density, would, if it were brought to the Earth, weigh 1,420 grammes—a little more than the weight of an equal volume of water. Now a cubic decimetre of Arcturus would weigh only the two-thousandth part of this, or 71 centigrammes, so that it would be eighteen times lighter than our atmosphere. More wonderful still, stars like Aldebaran are formed of gases lighter than hydrogen, and their substance is 900 times less dense than air at normal pressure !

How, in such conditions, can we picture to ourselves the physical state of these heavenly bodies ? No doubt, their central parts are dense enough for the occurrence there of calorific phenomena similar to those which we observe in our laboratories ; but what can possibly explain the incandescence of the infinitely rarefied outer layers ? We are totally unable to say.

Of the nature of these wonderful objects our solar system can give us no idea. Yet every one of them obeys the same laws that govern the bodies moving in our own small region of the heavens. Can this be proved ? The demonstration is perpetually before the eyes of astronomers as they mark the positions of the stars. Some stars when seen through a telescope appear to be double, and the fact

might be explained as merely the result of perspective, two different stars which are in reality far apart from one another being projected on almost the same point of the celestial sphere. But while this case is not infrequent, it also occurs sometimes that the system is physically double in the sense that there are two suns actually revolving round one another, or rather round their common centre of gravity, in accordance with the laws of Newton and Kepler. In this latter case the stars are called binaries.

Sometimes the two members of a binary system resemble one another closely, as in the case of our neighbour Alpha Centauri ; but sometimes, on the other hand, there is one

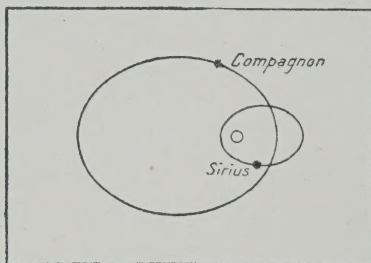


FIG. 57.—ORBITS OF THE TWO COMPONENTS OF THE DOUBLE SYSTEM OF SIRIUS. THE LITTLE CIRCLE WITHIN THE FIGURE REPRESENTS THE EARTH'S ORBIT ON THE SAME SCALE

principal star and one secondary, as in the system of Sirius, in which the companion star completes its revolution round the larger mass in a period of 50 years, and at a distance equal to 21 times the diameter of the Earth's orbit.

In former days there were very few binaries known, but recent progress in optical science, combined with tireless industry in observation, has shown that the number of these physically double stars is more than half of the total number. Unlike the single suns, such systems are very ill adapted for the formation of planets, for the good reason that the tides set up during the revolution

of the components attain to considerable amplitudes, and create regions of great instability.

We have a good instance of this in a class of binaries whose existence has been revealed to us by spectrum analysis. In their case the two members of the couple are so close to one another that we cannot hope to observe them as separate objects, even with the most powerful magnification ; but when we happen to be situated in the plane in which the system is revolving, eclipses on a greater or less scale must necessarily occur, and this is exactly what the spectroscope reveals. In some cases one of the stars is dark, and conceals more or less of its companion ; in others, the two stars are both bright but not equally so, and the curve of luminosity of the system as a whole exhibits several oscillations ; in both cases

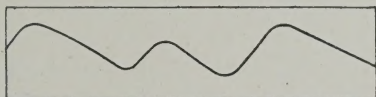


FIG. 58.—CURVE OF LUMINOSITY OF A VARIABLE STAR

alike, we can deduce the period of revolution, the amplitude of the light variation, the relative intensity of the rays, and consequently everything that is needed for the measurement of the intrinsic brightnesses, the distance apart, and even the masses of the two components. This has been done, for example, in the case of Algol (Beta Persei), the best known of the variable stars in which eclipses are produced by a dark companion ; or in the case of Beta Lyrae, in which the two components are of unequal brightness.

This discovery of spectroscopic binaries is one of the finest achievements of modern astronomical methods. Already in 1887 Miss Maury had observed in spectro-photographs the periodic duplication of certain lines, and had thence concluded that they were derived from two luminous bodies moving in orbits around one another ; but

the application of the Doppler-Fizeau principle has since made it possible for us to extend this method and to calculate the velocities of the moving components. In short, the spectroscope provides us to-day with information in regard to the smallest details of these systems, even though they are far too remote for our telescopes to be able to show them as anything more than apparently single stars.

It would be a mistake, however, to suppose that binaries are the only stars which vary in their brightness. All the stars are in greater or less degree like our Sun, for which, as we have seen, the curve of activity, as shown chiefly by the spots and prominences, has a period of about eleven years. But the intensity, as well as the period, of the phenomenon varies in different cases.

Some stars, like Mira (Omicron Ceti), have periods of about a year, and their variations closely resemble those of the Sun ; while others like the Cepheids (stars, that is to say, of the type of Delta Cephei) are affected by enormous periodic changes in the space of only a few days.

It has, moreover, been proved quite recently, and it is a curious fact, that in this last case there is a constant relation between the length of the period and the absolute brightness. For example, in stars of the Cepheid type we know that if the period is one day, the intrinsic brightness is 100 times greater than that of the Sun, for a period of four days it is 400 times greater, and 1,500 times greater when the period is ten days.

We thus become possessed of a most useful method for determining the distances of all the stars of the Cepheid type scattered over the heavens, since, in accordance with what was said at the beginning of this chapter, as soon as the real and apparent brightness are both known we are able to apply the new formulae.

The results which have been obtained are remarkable ; the labours of Hertzsprung, Pease and Shapley have shown that certain stars are far more remote than had been imagined in the last century, and distances of 20, 30, 50

thousand light-years are freely mentioned to-day. Shapley, who is an authority on the subject, has published in the last few years a series of papers on these fascinating problems.¹ His investigation has involved an immense amount of work, in which the distances of many of the Cepheids have been measured with great care in accordance with the new methods. Parallaxes are given of the order of $0.00017''$, or about one five-thousandth of a second, for Cepheids in Hercules, Boötes and Cygnus. While I am far from wishing in any way to criticise an undertaking which deserves so much admiration, I may be allowed to say here that I am still very sceptical as to the *exact* value of estimates like these. According to Shapley, the most distant Cepheids—those, namely, which are contained in the cluster numbered 7006 in the *New General Catalogue*—would be at a distance of some 220,000 light-years. In itself, there is no reason why such a figure should startle us, though the results of our older methods have not accustomed us to such distances ; but I repeat that a cautious attitude in the acceptance of the new values is advisable and indeed incumbent upon us. Can we be sure that, as we are told by those who use this method, the limits of error are no more than 20 per cent. of the figures obtained ? Everyone who has had practice in photometry knows how widely discrepant the results may be, and how delicate are the operations involved. We ought not, therefore, to be too hasty in taking the general indications furnished by the new spectroscopic method as an actual statement of the facts ; and this is proved by the circumstance that in the course of a few months, or at any rate a few years, Mr. Shapley has found himself compelled, like several other observers, to revise his first conclusions.

In a series of articles published in 1919 he even goes so far as to contradict certain opinions which the majority of astronomers have regarded as definitely established ; for example, he questions the existence of the galactic

¹ See HARLOW SHAPLEY : "Contributions from the Mt. Wilson solar observatory," Nos. 151-157.

ring, and considers that the Milky Way is the result of an optical illusion, thus asking us to go back to the old theory of the flat disc, or the "mill-stone" of Sir William Herschel.¹ Perhaps we should admit that it will probably be long before the last word on the subject is spoken.

But to return to the variable stars, the classifications which have been suggested for them cannot be properly called anything more than an aid to the memory ; for the fact is that, apart from the variations of stars of the type of Algol or Beta Lyrae, which are produced by eclipses, all the rest seem to range themselves, in their behaviour, along a continuous scale. Everything leads us to suppose that we are really in the presence of a quite general phenomenon which is connected with stellar condensation ; the way in which it is produced, its intensity, its period—all these, as far as classification is concerned, matter little. Different causes have, one after another, been put forward in the case of each different type ; but that implies too individual a way of regarding the facts, since it is precisely these special types which are artificial and cannot therefore provide any comprehensive solution of the problem as a whole. Whatever cause is operating must be of a general kind, and the same in all cases ; it must ultimately be the same as the cause which produces the sun-spots, and accounts for the periodic character of the solar activity.

We have already seen that this cause must be sought for in the chemical evolution of the elements—an evolution of which the mechanism has been revealed to us by radioactivity. We may recall Joly's hypothesis ² of the alternation of incandescent and geological phases in the history of our own globe ; and in any gaseous mass in process of condensation something of the same kind must occur. Without introducing any reference to radium, I may give the following account of the way in which I envisage the order of events.

¹ See "Bulletin of the British Astronomical Association," May 1919, pp. 205-206.

² See JOLY : *Radioactivity and Geology*, already quoted.

As soon as a state of incandescence is reached, the stellar mass begins to lose its heat by radiation. The amount of this loss increases as the fourth power of the temperature, and it is certainly greater than the heat which is gained by contraction or even as the result of atomic disintegration. The process, however, does not by any means affect the whole mass ; it concerns only the parts near the surface, where a sort of envelope is formed of relatively high stability. Gradually the heat is increased in the underlying layers in consequence of the formidable pressures to which they are subjected ; and the day at last arrives when this heat is sufficient to produce a disintegration of the atoms, which blaze forth afresh and burst the bounds of their temporary prison. There is no reason why this process should not go on continually until no further contraction is possible and there is no longer any heat for the mass to radiate ; but while this is happening, the intervals between the periods of explosive activity will increase, in proportion as the outer envelope gets more and more dense.

This theory, which I here put forward for the first time, seems to me the only one capable of explaining at one and the same time the phenomena of the variable stars, those concerned with the periodicity of suns, and also the geological phases in the course of which our Earth has been subjected to such vast upheavals. It is enough to admit disturbances which take effect only in the layers nearest to the outer boundary, to account for all the facts. Moreover, in the view of M. Marcel Moyer who has made a special study of variable stars, these facts are all in favour of such a way of conceiving the process.

The stars which fluctuate rapidly are very quick in reaching their maximum and more slow in reaching their minimum. It is established, too, that as in the case of our Sun, there is a secondary maximum which marks a temporary recovery during the descending part of the curve ; and a similar remark applies to the Cepheids. " It seems likely," says M. Moyer, " that in the case of these

suns the variations in the intensity of the photosphere are not only more abrupt but also more extensive than in the case of our own luminary, which fortunately for the conditions of life on the Earth is a quiet and peaceful star.”¹ These stars are evidently in their early youth ; but the same processes take place in the others, like Mira Ceti, which have attained to a more respectable age and for which the periods of variation are growing longer.

While in the former the brightness varies by one magnitude or thereabouts in the course of a few days, in the case of Mira the variation causes the star to change from the ninth to the third magnitude in about a year, and the spectrum at the minimum is entirely different from that at the maximum, just as has been found in the case of the Sun’s photosphere. “ Lastly, the stars in this category are all of a definitely reddish tint, and their spectral type is of the third or fourth class in Secchi’s classification ; they are gradually cooling, and their past splendour is revealed only by violent convulsions which occur at regular intervals.”²

The same theory holds good also for the temporary stars, or Novae, which are linked up with stars of the last-named types by the variables of irregular period like Betelgeuse or better still Eta Argûs which astronomers do not know how to classify.

It can hardly be necessary to remind the reader of what is meant by temporary stars. Everybody has had an opportunity in our own day of watching the famous Nova in Aquila which appeared on June 8, 1918, and from a magnitude invisible to the naked eye suddenly leapt to a brightness rivalling that of Altair, only to fade away gradually and be finally extinguished.

Since the famous star in Scorpio, which the celebrated Hipparchus took for a Nova but which was really only a comet, astronomers have registered about thirty of these remarkable sudden appearances ; but the fact is one of

¹ See M. MOYE : *L’Astronomie*, p. 341. Doin, Paris, 1913.

² *Ibid.*, p. 342.

frequent occurrence among the fainter stars which attract less attention. Many theories have been put forward at different times to explain the sudden arrival of such new stars. Some have supposed them to be due to the collision of two suns ; others have had recourse to the idea of two giant stars passing near enough to set up tidal disturbances in one another ; or again the suggestion has been made that a star may have had an encounter with a nebula or with a cloud of meteors. In an article which appeared in *Scientia*¹ in 1916, I showed that none of these hypotheses is in agreement with the observed facts, particularly with those which are revealed by the spectro-scope. At the present time, there is only one conclusion which seems to be forced upon us,—that what we see implies a disturbance affecting only the various envelopes of the star, that is to say the outer layers close to the photosphere, the chromosphere, and the inner corona.

It is, of course, quite evident that an explosion might be caused by a star passing through a region containing a great deal of meteoric material, and it may be that this is what happens on the confines of the Milky Way where the Novae chiefly make their appearance, or even in the heart of certain nebulae where they are often observed. But why should we look for an external cause, when the phenomenon is properly speaking only a special case of what is witnessed, in greater or less degree, in all the variables, to whatever type they belong ?

At the same time we have no right to dogmatise ; and even if we put aside the collision-hypothesis, we must admit that in the course of their swift journeys the stars must find plenty of obstacles spread in their way. And it cannot be denied that effects which closely resemble one another may be due to quite different causes.

¹ See Th. MOREUX : *Les Novae et la Constitution de l'Univers*, "Scientia," February 1916. In his address to the Société astronomique de France (see the "Bulletin" for July 1919, pp. 308 f.) M. de la Baume-Pluvinel gave an excellent summary of this article.

CHAPTER XV

STAR CLUSTERS

IF we examine the sky attentively on a clear night, the first thing that impresses itself on our minds is the tendency shown by great numbers of the stars to form more or less well-marked groups. Is this the effect of perspective, or are the groupings really there? The question was frequently asked by our predecessors, but unfortunately the data at their disposal fell far short of enabling them to answer it. To-day we are better equipped for doing so, and we are convinced that the grouping is real, though it is not always so pronounced as it seems.

Let us consider the Pleiades by way of example. Nine or ten stars are distinguishable by good eyesight, and with an opera-glass from 30 to 40 can be counted. In 1887 the brothers Henry obtained a photographic record of 2,326 stars, of which the faintest were of the seventeenth magnitude. It might therefore be supposed that the whole constitutes a group linked up by physical or mechanical relations, like binary or ternary stars, but this is not the case; a study of the movements of the separate members of the whole collection has proved that the stars which really belong to the Pleiades do not number more than a few score, and that these are journeying together towards one and the same region of the heavens in front of a field of faint stars which makes a distant background.¹

It is just the same with the Hyades, in which there are 34 stars travelling together in a roughly spherical formation which measures 14 degrees in diameter, with a clearly marked condensation in the centre. In some millions of

¹ S. NEWCOMB: *The Stars*, p. 79. J. Murray, London, 1902. See also the "Journal of the British Astronomical Association," January 1910.

years' time they will be seen as a more closely compacted cluster, of the same kind, no doubt, as the Pleiades, and will be situated in a region near the position at present occupied by Betelgeuse, which will have moved long before to another part of the heavens.

If we now provide ourselves with a telescope, the number of bright patches in the heavens becomes too great to be counted. Some of them, though not many, are visible to the naked eye, and in past times the general name of nebulae was given to them all; but with the improvement of optical instruments we have come to distinguish between resolvable and irresolvable nebulae according as the central part of the object can be resolved into bright points, each a separate star, or as it remains, in spite of magnification, a milky white expanse. Photographic and spectroscopic methods have made possible a greater degree of precision in the matter, and the clusters now seem quite different from the nebulae. We propose to study both in some detail.

Some early astronomers, notably Messier, Sir John Herschel, and d'Arrest, had already reckoned the number of what are called globular clusters, but their conclusions have little weight in comparison with modern investigations; indeed, little progress was made in the inquiry at all until recent years, when we became possessed of those new methods of which a brief account has been given earlier in this volume.

The first cluster to be studied was that in Hercules (13 Messier). From considerations based upon the variable stars which it contained—their curves of luminosity and the mean apparent brightness of certain groups of colours—Shapley calculated the distance of this strange formation, which long photographic exposures proved to be a collection of more than 30,000 stars. The parallax was decidedly less than the ten-thousandth part of a second, and the result which was provisionally obtained showed that light took some 100,000 years to travel the distance by which the cluster was separated from us. A

considerable flutter was caused in the scientific world when this announcement was made in 1915, and it would have been much greater if the thoughts of the larger part of mankind had not at that time been occupied with the Great War.

According to the learned researches of Newcomb, the estimates of the diameter of our Universe as represented by the Milky Way scarcely exceeded 6,000 light-years.¹ In 1914, Eddington was prepared to allow 10,000 as a maximum.² The Hercules cluster was therefore beyond these limits, and the occasion was seized for reviving Herschel's old theory of *island-universes*; in other words, the question was raised once again as to whether all the objects in the heavens did or did not form part of the galactic region, which it now seemed was become too small to contain them. If the answer was negative, it was evident that some of these objects, the clusters and nebulae perhaps, formed other milky ways which were independent of ours. For two years measurements were continually being carried out, and they seemed to be in favour of this latter hypothesis. Pease and Shapley more than once expressed themselves very distinctly as of this opinion, up to the year 1917.³

But in 1918 Shapley returned to the question once more, and the conclusions which he put forward, based as they were upon thousands of measurements which had been made with great care, merit the most serious consideration.

The American astronomer arrived at the conviction that the nearest of all the clusters which had been investigated was the one known as Omega Centauri. This was the one of which Sir John Herschel said, "This noble globular cluster is, beyond all comparison, the richest and largest object of the kind in the heavens."⁴ To the naked eye, it appears as a hazy star of the fourth magnitude, situated

¹ S. NEWCOMB: *op. cit.*, p. 319.

² EDDINGTON: *Stellar movements and the Structure of the Universe*, p. 32. London, 1914.

³ See "Astrophysical Journal," vol. XL, p. 434, 1914.

⁴ *Cape Observations*, p. 21.

at the edge of the Milky Way. Photographs show, however, that there, in a region hardly any larger than that of the full Moon, is a collection of distinct stars to the number of 6,400. These details are given by Bailey,¹ who asserts that this number takes account of those stars only which are distributed in the outskirts of the cluster, for those which form the brilliant spot of light in the centre are so crowded together as not to be separately distinguishable. Among them are 132 variable stars; and their periods, some of which are very short, have enabled us to form some idea of the distance of the cluster from the Earth.² Calculations have given this distance as 21,000 light-years, with a possible error of 30 per cent.

The cluster in Toucanus, though situated at probably an equal distance, presents a very different aspect. At least 10,000 stars are there packed together in a small spherical space of 11 minutes radius, and in its appearance it certainly marks the extreme limit of condensation. Bailey has counted 5,019 stars in this space, but unlike the cluster just mentioned it contains few that are variable.³

The Hercules cluster, which Messier had catalogued under the number 13, was described by him as a "nebula without any stars,"⁴ but it is on the contrary one of the richest clusters known. Mr. Palmer has counted 5,482 distinct stars, of average magnitude 13.5, on the photographs which he took of it with the great Crossley reflector, but the number of variables included is somewhat small. The discussion of the facts so far ascertained leads to the conclusion that the cluster is not situated at the distance of 100,000 light-years, as had been rather hastily announced, but at 36,000 only.

These figures, however, are nothing in comparison with those furnished by other celestial objects of the same kind. Shapley finds as the distance of the cluster in Delphinus, which is numbered 7006 in the *New General Catalogue*, the

¹ "Astronomy and Astrophysics," vol. XII, p. 691.

² See p. 220 f. for an explanation of the principle and method employed.

³ BAILEY: "Harvard Annals," vol. XXXVIII, p. 249.

⁴ *Conn. des Temps*, p. 233 (1884).

amazing figure of 220,000 light-years, or 25,000 times the distance of Sirius. I hasten to add that this cluster is the most remote of all those that we know.¹

Such results as these may seem to fit in with the theory of island-universes, but we must be careful to note that this is so only if we limit our own Universe to the dimensions which were generally accepted up to 1914. Since his more recent researches, however, Shapley himself

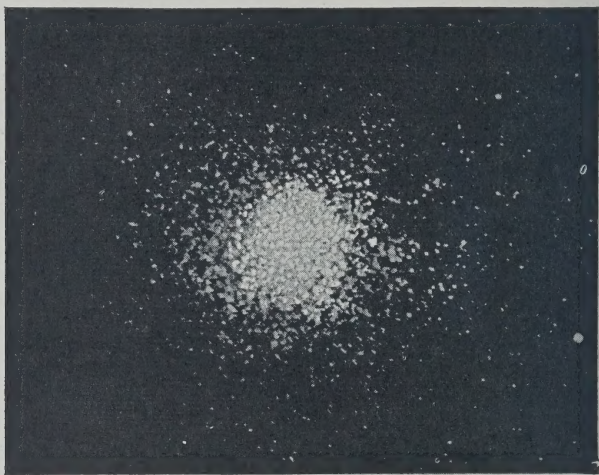


FIG. 59.—THE CLUSTER, OMEGA CENTAURI. (A PHOTOGRAPH OF THE CLUSTER AS A WHOLE)

has felt compelled to modify his earlier opinions. Of the Cepheids, which are contained in the Milky Way, most of those which it has been found possible to examine show distances far exceeding the low limits formerly assigned by Newcomb or Eddington to the great galactic ring; and consequently Shapley has not hesitated to write the following extremely suggestive words: "Any external

¹ For all these figures, see HARLOW SHAPLEY: *Mt. Wilson Contr.*, Nos. 151-157, 1918.



FIG. 60.—THE CLUSTER, OMEGA CENTAURI. (A PHOTOGRAPH OF THE DENSEST PART)

'universe' must now be compared with a galactic system (that is to say, our own) probably more than three hundred thousand light-years in diameter."¹

On the other hand, as our Sun is not placed centrally in the Milky Way, but is at a distance from the centre of about 65,000 light-years, it may be seen at once that the whole system might very well contain the globular clusters, most of which are distributed, from our point of view, on the same side of it.

It must, however, be remembered that the Galaxy is generally represented by a sort of disc, either annular or ellipsoidal; hence the conclusions which we have just stated would not hold good unless the globular clusters were within, or near, the boundary of a region for which the axis of the equatorial plane is some thirty times longer than the maximum thickness as represented by the axis perpendicular to this plane. Now an examination of the catalogues shows that if, in the case of the 245 objects at present known, we take the average of their positions referred to the galactic plane, the clusters are found to be distributed in two belts whose angular distance from this plane is about 30 degrees.²

The 69 clusters recently examined at Mount Wilson are still more suggestive. They show that the globular clusters are not in the Milky Way, if that is the right way of expressing it, but they are all either above it or below, and the maximum of condensation is reached in regions which are situated at a distance of about 13,000 light-years from the median plane, corresponding to actual latitudes of 7 or 8 degrees north and south. We know, however, one cluster—that in Coma Berenices (*New General Catalogue*, 4147)—which forms an exception to this general rule. Perhaps it is really a nebula, but this can be settled only by future research.

Another subject at present under discussion is that of the Magellanic Clouds, which look like large detached

¹ *Mt. Wilson Contr.*, No. 157, 1918, p. 2.

² "Mem. Royal Astr. Soc.," vol. LX, part 5; "Nature," Sept. 2, 1915.

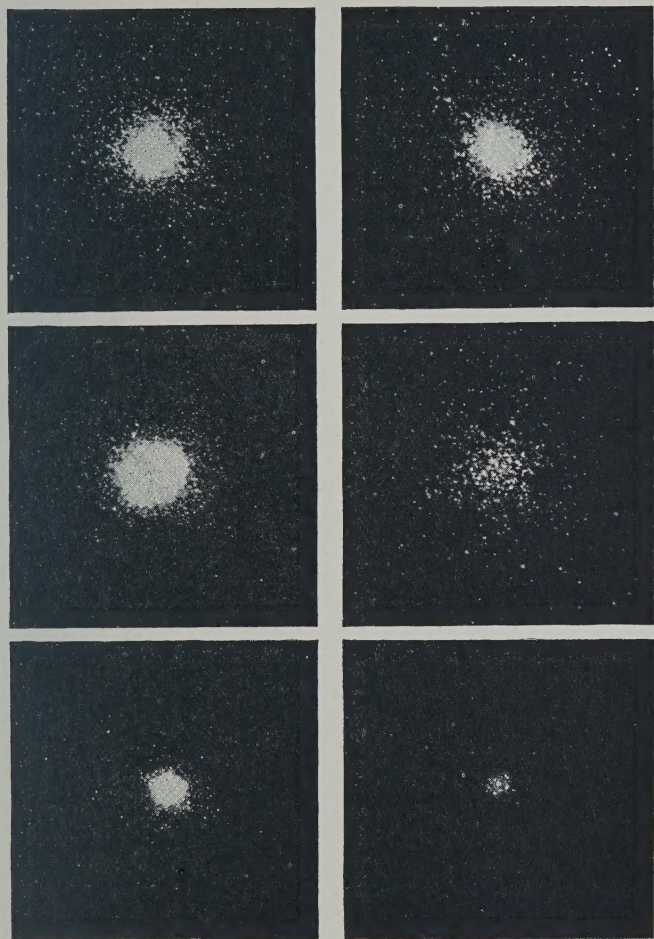


FIG. 61.—TYPES OF STAR CLUSTERS. THOSE SHOWN ARE THE ONES
SITUATED IN
CANES VENATICI,
HERCULES,
TOUCANUS (centre of cluster),
LIBRA,
OPHIUCUS,
TOUCANUS (general view)

fragments of the Milky Way. These strange formations, known as the smaller and the larger cloud, exerted a great fascination over Sir John Herschel at the time of his observations at the Cape of Good Hope. In the words of Humboldt, they constitute a unique phenomenon in the celestial world ; “ the larger and the smaller clouds,” he wrote, “ add still more to the picturesque charm of the southern hemisphere,—I might almost say, to the beauty of the landscape.” So brightly do they shine in Doradus and Hydrus that they cannot fail to attract the notice of the most careless observer.

The larger cloud spreads over an area of 12 degrees square, which is about 200 times as large as the apparent surface of the full Moon ; the size of the smaller cloud is one-fourth as great. In bright moonlight the latter disappears from sight, but the former still remains clearly visible.

Beside them is a space almost empty of stars, as if they had exerted an attraction over all the objects in their neighbourhood and swallowed up, to their own great advantage, the materials moving within a range of thousands of millions of miles. “ Around the Nubecula Minor especially,” said Herschel, “ is one of the most barren regions of the heavens ; . . . access to it is on all sides through a desert.” But as soon as the telescope is turned upon this mysterious field, it exhibits a richness bewildering to the most fertile imagination. We find ourselves gazing at a miniature universe, with its own constellations and clusters, and its nebulae sprinkling the ground of the sky with luminous patches.

In the presence of such a munificent spectacle, Sir John Herschel despaired of being able to grasp or define its extraordinary complexity. He counted on the whole, in the two objects, not less than nearly 800 stars, 72 star clusters, and 316 nebulae. Further surprises were in store when photographic methods came to be employed : in one nebula alone out of the hundreds which are contained in the Nubecula Major, our photographs show an astound-

ing collection of 300,000 different suns ; the Nubecula Minor is almost equally rich, and 280,000 stars have already been counted in it.

A study of the variables included in these vast stellar regions has made it possible for us to obtain a provisional idea as to their distances, and it is estimated that the two Magellanic Clouds are something like 62,000 light-years away. Moreover, as the apparent diameter of the larger cloud is 7 degrees, its real diameter must be one-eighth of its distance from us, whatever that may be ; so we may conclude that light takes about 8,000 years to travel from one side of it to the other, while 4,000 years would be taken in the case of the smaller cloud, for which the linear dimensions are about half as great. These figures are not precise, nevertheless they prove that the size of these celestial islands is comparable with that which we were content not long ago to assign to our own Galaxy. At the same time, in view of figures like these, we can no longer think of comparing the Magellanic Clouds with our Universe as we now know it ; as I have already stated, they resemble it only in miniature. It is very probable, therefore, that we have here large fragments which have become detached from our Milky Way, and that these particular collections of clusters are really linked up with all the others which we have been considering. The mean value of the distance measurements for such globular clusters as those in Hercules or Canes Venatici is four or five hundred light-years ; we might therefore complete our picture by saying that these represent islands strewn along the edges of our Galaxy and belonging to it, while the Magellanic Clouds are rather to be compared to a distant archipelago which is under our protection.

Thus the most recent researches leave us in no doubt as to our conclusion. At the present time there cannot possibly be any question of reviving the theory of island-universes, at least in the form in which it presented itself to the minds of those who propounded it. If by *islands* we mean universes quite distinct from ours, and comparable

in size with the Milky Way which represents it to our eyes, the globular clusters are not capable of filling such a position ; but on the other hand, we may very well regard them as islands belonging to our continent—each a kind of self-governing dominion of stars, which yet acknowledges the sovereignty of that imposing system to which our own Sun belongs.

As to the way in which this sovereign control is exercised, the study of the nebulae will help us to understand it more exactly, while at the same time it will confront us with one of the most difficult problems that the human mind can assail.

CHAPTER XVI

NEBULAE

SIR WILLIAM HERSCHEL, in the course of his survey of the heavens, was instinctively led to place the nebulous objects which his powerful telescope revealed to him in a class by themselves. As Miss Clerke wisely remarks, the founder of modern astronomy "could not see without at the same time setting in order what he saw; and the law of order that commended itself to him was founded on an evolutionary principle."¹

By applying the laws of gravitation to the masses which he considered to be gaseous, Herschel concluded that condensation or contraction marked the ultimate end to which such objects were bound to come at last. The great irregular nebulae, like the one in Orion, represented in his opinion the earliest stage of all—the primitive chaotic state in which, as the result of frictions and collisions, the elements were gradually collected and by slow degrees assumed more precise forms. Thus were evolved the regular nebulae, and these finally developed into planetary nebulae or nebulous stars.

Although probably true in its broad outline, Herschel's classification has not been confirmed by modern discoveries. There does not appear to be any continuity between the regular nebulae and the so-called planetary ones. This term, it is well known, was invented by Herschel as a name for those circular objects which shed a uniform light and suggest the appearance of a flattened disc.

Moreover, as instruments were made more perfect, and photographic investigation went on, it became abundantly clear that the apparent shape and structure of a nebula

¹ MISS CLERKE : *Modern Cosmogonies*.

depended upon the magnification and the length of the exposure. Thus, to take one example, several planetary nebulae appeared as annular ones as soon as they were examined through the great telescope of Lord Rosse.

To this disconcerting list of causes which have modified the views put forward by Herschel, another must be added, namely spectrum analysis. The first impression which was created by this new process was that anything and everything might be expected from it. We can understand better with what enthusiasm the spectroscope was turned to for the settlement of outstanding questions when we read the reflexions of Sir William Huggins on the first observation which he made by its means : " On the evening of August 24, 1864, I turned the spectroscope for the first time towards a nebula in Draco. I looked. . . . There was no spectrum of the kind that I was expecting ! Nothing but a single bright line. At first I thought that the prism must have got displaced. . . . But directly afterwards I saw the true explanation."

The astronomer knew, of course, that every metal in an incandescent state gives a continuous spectrum, but that when such a glowing mass is seen through a gaseous atmosphere, this is crossed by a series of black lines, while the light coming from the luminous gases themselves yields a spectrum which consists only of clearly marked lines, very bright and distinct.

Huggins could not therefore make any mistake. " A more careful examination," he adds immediately after in his memoir, " revealed to me two other bright lines towards the blue end, the three lines being separated by intervals which in comparison were black. The problem of the nebulae was solved. Light itself had sent us the answer—that a nebula consists not of a multitude of stars but of a luminous gas." This wonderful discovery inaugurated a new era in the conquest of the heavens.

We have found out since the time of Huggins that the principal lines in the spectrum of the nebulae are due to hydrogen, helium, and an element unknown in terrestrial

chemistry to which astronomers have given the name *nebulium*. At the present time the number of lines which can be detected is increasing with the improvement of the methods employed, and more than seventy have already been observed.

Meanwhile, even before the death of Huggins, it appeared that things were not quite so simple as they had seemed at first, and it had been demonstrated that certain nebulae yielded a continuous spectrum crossed by dark lines; hence these objects were nebulae surrounding either blazing suns or at the least solid particles of some kind, or perhaps gases subjected to great pressure since matter in that state also exhibits a continuous spectrum.

It can be seen, therefore, that even with the help of the spectroscope the classification of the nebulae presents an insoluble problem. Still, for lack of anything better, modern astronomers have adopted the following division:

(1) Nebulae whose spectra consist of bright lines; this class comprises most of the irregular and planetary nebulae, all of which are probably gaseous;

(2) Nebulae which yield a faint continuous spectrum traversed by dark lines; almost all the objects in this category belong to the class of spiral nebulae, of which a few examples have been observed with the great Rosse telescope, and which is now proved by photographs to be by far the most widely spread type of nebula in the heavens.

This classification, however, does not aim at any mathematical accuracy, and the two categories are by no means exclusive. The spiral nebulae, for example, often furnish both types of spectrum; such are those numbered 598, 1068, 5236, etc., in the *New General Catalogue*.¹

This proves once again that we are dealing with objects which are actually evolving—with nebulae which, starting from a gaseous or perhaps a pulverulent state, slowly arrive at the condition of a star. And thus we are brought back to the dominating idea of Sir William Herschel.

¹ See M. SLIPPER: Proceedings of the Philosophical Society of Philadelphia, vol. LVI, No. 5, pp. 403 f.

But how great would be the astonishment of that famous astronomer if he could see our celestial photographs! To-day, most of the nebulae like the one in Orion, and the annular nebulae like those in Lyra have revealed to us their spiral shape. The theory that the ring nebulae form satellites or even planets—that old doctrine so dear to the people who invent systems of cosmogony—is no longer to be found written across the sky. Born in the mind of Laplace, it has been discredited by long-exposure photography.

Nevertheless, when we turn to consider the planetary nebulae, which in regard to their spectra are so closely akin to the gaseous, we cannot trace the law of continuity. They seem, for the moment at any rate, to refuse to conform to the rules of that theory of cosmic evolution which our instinctive love of order, both in time and space, makes us find so attractive.

Like the globular clusters which we studied in the last chapter, they seem to have a liking for the outlying parts of the Milky Way, and therefore they certainly belong to our Universe.

Most of the other types are definitely spiral in shape, and their relations with the Galaxy seem rather of a negative character, in the sense that the law of their distribution is the opposite of that which holds for the stars, for they become more and more numerous as we approach the galactic poles. This rule is not based, as the early catalogues might lead us to suppose, on a small number of objects; for since the days of Sir William Herschel, who counted 2,500 nebulae, we have come to reckon them by thousands. One of the first results which Keeler obtained from his photographic investigation with the Crossley telescope went to prove that the number of nebulae to be observed in the whole of the heavens must be about 120,000. But we are now convinced that telescopic mirrors like the one at Mount Wilson, with its diameter of 100 inches, are capable of showing us, at the lowest estimate, something like a million nebulae, and of

these the large majority conform to the definitely spiral type.¹

Of what do these wonderful formations consist? To tell the truth, the facts which have hitherto been collected do not justify our forming any certain conclusion. The light which comes from these objects is extremely faint, and their observation is a task of great delicacy. If we are gradually to obtain more complete information, it can only be through the use of photographic methods in studying them, and these methods are of comparatively recent date.

A few facts, however, seem to have been established beyond doubt. Thus the spirals almost always consist of two branches which originate at the two opposite ends of a diffuse and sometimes elongated nucleus.

Long exposures, occasionally extending to 80 hours, give us a mass of details, but these are not easily susceptible of interpretation. Spectroscopic examination justifies the statement that the spiral nebulae are animated by very complicated movements of rotation: thus it would seem that direct and retrograde rotations have both been observed in the same nebula.²

In the past it was generally admitted that there was indisputable evidence of condensation towards the centre, under the influence of gravitation; but we now suspect that side by side with an action of this, so to say, classical kind, an important place remains for the action of repulsive forces; the outermost parts of the spiral nebulae show a marked tendency to draw farther away from the centre,³ possibly under the influence of the pressure of radiation. We should thus have the beginning of an explanation of the almost incredible fact that the spiral curves of the nebulae seem to be wrapped round the nuclei in such a way that they revolve in the opposite direction to that of a

¹ See the article by CURTIS in "Publications of the Astronomical Society of the Pacific," April 1918.

² See "Revue du ciel," pp. 90 and 135 (1917).

³ See the observations of VAN MAANEN at Mount Wilson, 1918.

hydraulic turbine !¹ Truly, we understand as yet almost nothing of the mechanism or the nature of these wonderful objects.

We have seen that the spiral nebulae are rare in the neighbourhood of the Milky Way, and that they seem as if they were trying to escape so as to group themselves near its poles.² This, as we have said, is one of the characteristics by which they differ from the clusters, and we must now call attention to another. The result of all the measurements which have been carried out upon the star clusters goes to show that they are approaching the Milky Way ; their velocities are enormous, far greater than the average of the velocities observed in the case of the stars. In the table given by Shapley,³ we find *radial* velocities of approach amounting to 140, 185 and even 215 miles per second, and this takes no account of the tangential velocity with which the radial has to be compounded ! Is the same thing true of the nebulae ? The question is much more difficult than it seems, because it is linked up with a number of doubtful assumptions.

For one thing, the spectrograms are faint, and sometimes the lines are indistinct, so that their positions are difficult to measure. For another, it is possible that even the bright parts of the nebulae are not stars, but gases subjected to great pressure ; and in that case the observed radial velocities may be misleading, as has been shown in the case of the Novae. However that may be, it is certain that whereas Keeler, in 1890, found that the radial velocities did not exceed 40 miles per second, recent measurements give as a rule much greater values. Slipher has deduced from the examination of the spectra of 25 nebulae an average velocity of 350 miles per second, which far exceeds that of the stars.⁴ These results have been confirmed by

¹ See M. SLIPHER's article quoted above, p. 239 note.

² The small spiral nebulae are plainly most numerous in the zone which surrounds the poles of the Galaxy, and extends, according to CURTIS, to 30° galactic latitude (see the article referred to above, p. 241 note).

³ See "Astrophysical Journal," 1918, p. 12.

⁴ See M. SLIPHER : *The Nebulae* (the article already referred to).

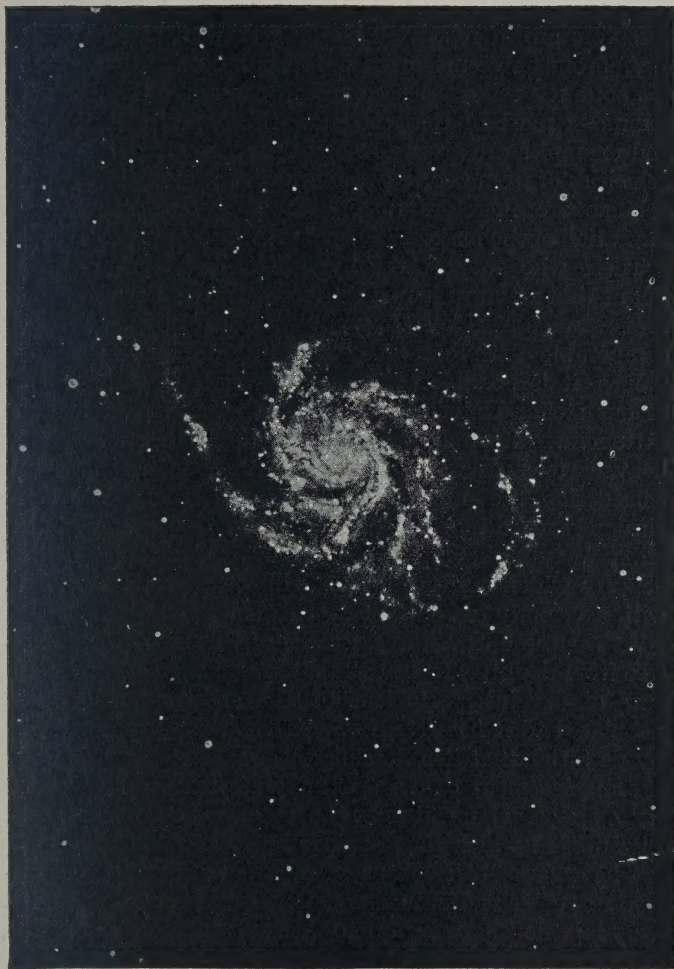


FIG. 62.—PHOTOGRAPH OF A SPIRAL NEBULA IN URSA MAJOR

other astronomers, and the results obtained by different observers are in relatively close agreement. The nebula in Andromeda seems to be approaching us with a speed of about 180 miles per second, but cases like this are not common ; most of the rest show the opposite tendency, and examples are given of nebulae receding from us with velocities of from 600 to 750 miles per second. The spiral nebulae are therefore rushing away from the immense formation of the Milky Way, and making for its poles.

Those who support the hypothesis of island-universes tell us that we have here a convincing reason for the belief that nebulae of this class really represent other universes comparable with ours. By selecting the most reliable values, it is possible even to investigate the movement of our stellar Universe in relation to the others, just as astronomers have long ago determined the spot in the heavens towards which the solar system is travelling by considering the proper motions of the stars. The conclusion reached by similar methods in this case is that the Milky Way is moving as a whole towards a point in the heavens which is situated in the direction of Capricornus, with a velocity of 400 miles per second ! ¹

At the same time the existence of this new apex is not free from doubt. To be certain of it we should have to be sure of our interpretations of the spectrograms of the nebulae, and it has recently been very wisely pointed out by de Sitter that if Einstein's theory of relativity is true, the displacement of the spectral lines may quite well be only apparent, for it may be chiefly due to the great distances at which the nebulae are situated.²

The argument, it will be seen, does not favour the supporters of island-universes ; they have, however, tried very ingeniously to turn it to their advantage. According to them, the admission of these immense distances as revealed by the spectroscope definitely proves that the nebulae, or at least those belonging to the spiral class, are

¹ See Th. MOREUX : " *Revue du ciel*," 1919, p. 643.

² " *Monthly Notices*," vol. LXXVIII, p. 26.

beyond the limits of our Galaxy. Hence the true solution of the problem depends upon the determination of the parallax of the spirals.

Here we find still greater uncertainty awaiting us. According to Kapteyn, the nebula in Orion, which is probably the remains of a great spiral formation whose traces can still be discerned, is only 600 light-years away.¹ Van Maanen, from direct measurements made with the 60-inch telescope at Mount Wilson, gives the distance of the famous nebula in Andromeda, as well as of those in Canes Venatici, as 650 light-years.² If we accept this figure, it would follow that the greatest diameter of the nebula in Andromeda has a value of not more than 40 light-years. Even if we take the distance to be 80,000 light-years, as calculated by Véry, still this is less than the figure which Shapley adopts for the dimensions of the stellar system in which we are ourselves immersed, and the nebula in Andromeda remains a small object in comparison with the whole.

It is clear, from the existence of such divergent views as these, that the discussion is by no means closed, and there are even to be found extremists—indeed, they can be met everywhere—like MM. Lindemann, who have suggested for the nebula in Andromeda a diameter of 50,000 light-years, and a parallax so minute that the distance would be increased to a *million* light-years—and this in the case of a nebula which is one of the nearest that we know! ³

“The problem of the spirals,” as Mr. Macpherson has said, “is at present far from solution; and judgment on their exact status must be suspended until we are in possession of more detailed knowledge.” ⁴

There is one fact, at any rate, of which we must take account—the distribution of the nebulae around the poles of the Milky Way. If these objects are in no way related

¹ See “Mount Wilson Contributions,” No. 147.

² *Ibid.*, No. 156.

³ See an article by MACPHERSON in “The Observatory,” September 1919.

⁴ MACPHERSON: *ibid.*

to the Galaxy, such a distribution is inexplicable. It has actually been propounded that there exists some interstellar medium, enveloping the Galaxy as it were with an opaque cloud which conceals from our sight such faint objects as the nebulae projected on the celestial sphere near its borders; but this hypothesis is untenable, and cannot be reconciled with other and established results.¹ Until further information is available, therefore, we must regard as probably correct the view which sees in the nebulae objects forming part of our Universe.

How, then, is their presence to be explained? We suggest a somewhat bold hypothesis which satisfies the mind's eager desire to reduce the facts to order, though at some risk, it must be confessed, of not being true in every detail.

I conceive the entire Universe to be enclosed within a spherical space, through which at first all existing matter was spread. As the result of some process of which at present we have no conception, these materials came to be collected in the equatorial zone of this enormous sphere, and by their evolution gave birth to stars, stellar systems, our own Sun,—in a word, to all the objects which constitute our Milky Way properly so called. But this, it cannot be doubted, still includes portions which are not yet condensed, clouds of gas or of meteors, and these give rise to the apparently empty spaces either in the Milky Way itself or around the stars and the galactic nebulae.

Particles which were sufficiently large would be subject to the law of gravitation, and so would be drawn in to the stars; but those which were lightest would be acted upon by the pressure of light and would be quickly dispersed towards the poles of the sphere, where their massing together would bring the nebulae into existence. After a prolonged sojourn in those remote regions, and in proportion as the work of condensation had been accomplished, the nebulae would become star clusters; they would then once more be attracted by the equatorial disc

¹ See "Mount Wilson Contributions," No. 152.

and would commence their return journey. Retaining the spherical shape which they possessed in high galactic latitudes, the globular clusters, on arriving in the neighbourhood of the equatorial zone of stars, would come under the dissolving influence of the whole system, and the resulting effect would be such as we have already observed in the case of the comets, which change by slow degrees into swarms of meteors.

We do, in fact, see spherical clusters in an advanced stage of condensation in high galactic latitudes. Nevertheless, a large number of them preserve traces of their origin, and the stars which surround them or are situated in their outskirts are still disposed in spiral branches. But as soon as these clusters approach the Milky Way, they are transformed into open clusters, and the stars composing them tend to be dispersed ; this has occurred in the well-known cases of the Pleiades and the Hyades—the latter only 130 light-years away. There is therefore room for thinking that in the far-distant future all the clusters will change their shape, and will gradually be incorporated in the great galactic girdle, which will snap them up and transform them into star streams like the one to which our own Sun belongs. The equatorial plane of the original sphere would thus gradually tend to become the densest part of the space through which the materials were first of all dispersed ; and just as we see water-vapour rising from the surface of the ocean and carried away by atmospheric currents, to come back at last to its point of departure after a lengthy journey in the course of which it is condensed, so the particles thrust forth by the solar masses in their ceaseless ebullition would regroup themselves so as to give birth in high latitudes to the nebulae, which would be transformed in their turn into clusters and be attracted again by the formidable mass of the entire Galaxy.

Does the reader think that these are rash and unprofitable speculations ? Perhaps they are, but the feeble spark of intelligence which burns in us is surely our best excuse.

"It is impossible," said Henri Poincaré at the outset of his lectures on past systems of cosmogony, "to contemplate the spectacle of the starry Universe without asking oneself how it was formed. Possibly we ought to wait to look for a solution until we have patiently accumulated the necessary materials, and have thereby acquired some good hope of discovering it; but if we were thus controlled by the dictates of reason,—if we were merely curious without being impatient,—the probability is that Science would never have been created at all, and that we should have been satisfied with the task of living our petty lives. The fact is, however, that our mind imperiously demands this solution before it is really within our reach, and while our intelligence is directed only by such faint gleams of light as allow us to make guesses at the truth rather than to attain it."¹

Since those words were written in 1911, our acquisitions of knowledge have evidently been increasing, but it is the characteristic of Science to open out to us a horizon that knows no limits. Duclaux once said, in a whimsical moment, "It is because Science is never sure of anything that it goes on advancing." Far from endorsing this opinion, I believe on the contrary that the more progress we make in the study of nature, the more clearly do we perceive how wide are the fields which lie open to our investigation, and the more numerous become the problems and the enigmas confronting us at every turn along the paths of knowledge. Yet we know full well that apart from our changing opinions and our transient theories, there are laws to which all matter is subject—laws which we did not make and which we cannot alter; and it is precisely because he believes in the universal sway of these laws that the man of science devotes his life to their research.

It is evident to-day that it would be mere madness to pretend that matter could have imposed its own laws upon itself. Even if we admit that the ultimate particles

¹ H. POINCARÉ: *Leçons sur les hypothèses cosmogoniques*, preface. Hermann, Paris, 1912.

are endowed with some kind of consciousness, we can with difficulty imagine the procedure of a universal *referendum*, a sort of plebiscite tending to a general agreement on the part of materials which are evolving in systems separated from one another by intervals that are reckoned in hundreds of light-years.

On the other hand, it is not clear to our intelligence why the laws which govern matter should not be other than they are. Do not transcendental geometry and rational mechanics continually suggest to us new forms of what might be? Then why, in our Universe, does this thing happen rather than that? No one can answer the question; but it follows very plainly from these considerations that the laws of reality cannot in any case appear to us as rigorously necessary; rather, contingency is of their essence.

Our conclusion, then, is that far from evolving as it likes, matter is on the contrary urged by necessity. A higher force, and one quite distinct from it, has imposed upon it a determinate mode of action. Thus, behind the transparent veil of phenomena, there stands revealed the part played by Creative Thought, always youthful, always present, always at work, presiding over the birth of the atom, even as it directs the evolution of the farthest star lost in the unplumbed immensity of space.

INDEX

- Abbot, 12
 Aberration, 60
 Abraham, Max, 47
 Acceleration of Moon's orbit, 74
 Adams, J. C., 157 f.
 Adams, W. S., 214
 Airy, 157 f.
 Albedo, 43
 of Mercury, 43
 of Saturn, 140
 of the Moon, 84
 Aldebaran, 217
 Algol, 219, 222
 Alps (lunar), 80
 Altair, 224
 Alternation of geological and incan-
 descent phases, 37, 90, 222
 Ampère, 47
 Andromeda, nebula in, 244 f.
 Andromedes, 193
 Annular nebulae, 210, 238, 240
 Antares, 212, 217
 Antiapex, solar, 206
 Antoniadi, E. M., 15, 106, 108
 Apennines (lunar), 80
 Apex, solar, 206
 Aquarids, 193
 Aquilæ, Nova, 224
 Arago, 97 f., 151 n., 153, 188 ff.
 Arcturus, 205, 208, 216 f.
 Aristarchus, 85
 Aristotle, 132
 Arrhenius, 25, 52, 69
 Asteroids, Chap. VI *passim*, 176
 connexion with comets, 120
 inclinations, 120
 Martian group, 121
 their eccentricities, 120 f.
 Trojan group, 121, 167
 Astronomical unit of length, 162
 its calculation, 163 ff.
 Atmosphere :
 effect of the Earth's in absorbing
 heat, 12
 of Jupiter, 136
 of Mars, 108 ff.
 of the Moon, 81, 83
 of Venus, 50
 Atmospheric electricity and earth-
 quakes, 70 f.
 tide, 97 f.
 Atomic energy, 26 f.
 Auroræ, 18, 21, 69
 on Venus, 52 f.
 Axis of Earth, periodic movement
 of, 57 ff., 97
 Babinet, 187, 188 n.
 Bailey, 229
 Barnard, 133, 159
 Base line, 163 f., 201
 Becquerel, 26
 Belot, E., 195
 Bessel, 40, 153
 Betelgeuse, 216, 224, 227
 Bianchini, 51
 Biela, 191, 193
 Biela's comet, 178, 184, 191, 194
 Binary stars, 217 f.
 Birkeland, 69
 Bode, 117, 122, 151
 Bode's law, 117, 122, 149, 155, 158, 162
 Bond, 142
 Boss, Prof., 207
 Bouvard, A., 151 n., 153
 Bradley, 60, 137 n.
 Bredichin, 186
 Bremiker, Dr., 157
 Briner, 25
 Brooks's comet, 181
 Brorsen's comet, 179
 Brückner's law, 17
 Bruys, 190
 Calixtus III, Pope, 187 ff.
 Canals on Mars, 102 ff., 111
 Canes Venatici, nebulae in, 245
 Capella, 202
 Capture hypothesis, 135, 149, 178
 Carrington, 3, 33, 127
 Cassini, 51, 128, 141, 145, 165
 Cassini's division, 141 ff., 147
 Centauri :
 Alpha, 202, 218
 Omega, 228 f.
 Proxima, 202

Cepheids, 220 f., 223, 230
 Ceres, 117 f., 123
 Ceti, Mira, 220, 224
 Challis, 157
 Chambers, 17
 Changes on Moon's surface, 93 f.
 Charlois, 119
 Cheseux's comet, 186
 Chromosphere, 7 f., 17, 29
 vortex movements in, 31 f.
 Circuses (lunar), 78 ff., 91
 Clairaut, 155
 Clavius, 78, 132
 Clerke, Miss, 120, 211, 237
 Climate :
 of Mars, 109 ff.
 of Mercury, 43
 of Venus, 51 f.
 Climatic cycle on the earth, 16 f.
 dependent on the Sun, 13 f.
 Cloud belts :
 on Jupiter, 126 f.
 on Saturn, 140
 Clusters of stars, Chap. XV *passim*,
 242
 globular, 227 ff., 240
 Colin, Fr., 98
 Coma Berenices, 232
 Comets, Chap. XI *passim*
 constitution, 180 f., 183 f.
 eccentricities, 175
 families of, 176, 178 f.
 groups of, 179, 194
 inclinations, 175
 Jupiter's attraction of, 176, 178
 mass, 181
 nucleus, 180 f.
 orbits elliptic, 172 ff.
 retrograde, 176
 size, 180 f.
 tails, 184 ff.
 their connexion with asteroids,
 120
 Commensurability, Kirkwood's law
 of, 122, 146
 Compass, deviations of, 18 f., 21
 Conic sections, 39
 Conjunction, 50
 Copernicus (astronomer), 40
 Copernicus (lunar crater), 79, 85
 Corn, yield of, in France, 14, 21
 Corona, 8, 30
 periodicity of, 11, 36
 rotation of, 34
 Coronium, 10
 Craters (lunar), 78 ff.
 Crookes, 27
 Crust, movement of Earth's, 58 f.,
 67

Curie, M. and Mme., 26
 Cyclone theory, Faye's, 32 f.
 Damoiseau, 191
 d'Arrest, 119, 227
 Daubrée, 87
 Dawes, 102
 de Boismenu, E., 197
 Dechevens, M., 71
 Deimos, 114
 de la Baume Pluvinel, 183
 Delambre, 64
 Delphinus, cluster in, 229 f.
 Denning, 40
 Density :
 of the Earth, 100
 of Jupiter, 126
 of Mars, 100
 of Neptune, 159
 of the stars, 217
 of Uranus, 152
 of Venus, 49
 de Plantade, 42
 de Saron, B., 151
 de Sitter, 244
 Deslandres, 7, 29, 68 f.
 Deviations of compass, 18 f., 21
 de Vico's comet, 179
 Discovery of Neptune, 153 ff.
 of Uranus, 117, 150 f.
 Distance :
 of nebulae, 227 ff.
 of the planets from the Sun, 170
 of stars, 200 ff., 214, 220 f.
 of the Sun, 162 ff.
 Dörfel Mountains (lunar), 80
 Donati's comet, 175, 186
 Doppler-Fizeau method in spectro-
 scopy, 40, 204 f., 220
 Draconids, 193
 Draper, 189
 Duclaux, 248
 du Ligondès, Colonel, 93
 Earth, Chap. III *passim*
 climatic cycle, 16 f.
 currents, 67
 magnetic pole of, 68
 Moon's effect upon, 58, 61 f., 95 ff.
 polar compression, 66
 radius, 65 f.
 rotation not constant, 55 ff.
 shape, 63 ff.
 speed in orbit, 60
 tetrahedral theory of, 66
 Earthquakes, 19 f., 22, 58, 70 f., 97
 connexion with atmospheric elec-
 tricity, 70 f.
 Easton, 210 f.

- Ebert, 69
 Eccentricity, 39, 120
 of asteroids, 120 f.
 of comets, 175
 of Earth, 59 f.
 of Halley's comet, 39
 of Jupiter, 126
 of Mars, 100
 of Mercury, 120
 of the Moon, 72
 of Tempel's comet I, 120
 of Uranus, 152
 of Venus, 39
 Eclipses, 61, 74
 of Jupiter's moons, 136
 Ecliptic, 61 f.
 Eddington, A. S., 228, 230
 Einstein's theory of relativity,
 47 ff., 75, 244
 Electro-magnetic theory of light,
 Maxwell's, 46, 48
 Ellipticity, 66
 Elongation, 50
 of Mercury, 39
 Encke, 142, 165
 Encke's comet, 46, 178
 Encke's division (in Saturn's ring),
 142, 144
 Equation of light, 138
 Equatorial acceleration :
 of Jupiter, 36, 127
 of Saturn, 36, 139
 of Sun, 3, 30, 33, 35, 127
 Eros, 121, 166 ff.
 Eruptions, volcanic, 20 f., 37, 67
 Esclagon, E., 49
 Euler, 74
 Europe and Asia, mountains of, 37
 Evaporation, effect on Earth's axis
 of, 58
 Evolution of stars, Chap. XIV
 passim

 Fabry, L., 173 ff.
 Faculae, 12
 Families of comets, 176, 178 f.
 Faraday, Sir M., 47
 Faye, 4, 18, 24 f., 134, 189
 his cyclone theory, 32 f.
 Fayet, 173 f.
 Fire-damp, outbreaks of, 19
 Flammarion, 189
 Flaugergues, 42
 Fleury, 190
 Flocculi, 8

 Galaxy. *See* Milky Way
 Galileo, 95, 131 f.

 Galle, Dr., 156 f.
 Gambart, 191
 Gledhill, 128
 Globular clusters, 227 ff., 240
 Goldstein, 69
 Gonzalez, 16
 Gore, 160
 Gould, 211
 Grant, R., 189
 Gravity, value of :
 on Jupiter, 130
 on Mars, 100
 on the Moon, 79, 81
 Great Red Spot on Jupiter, 128 f.
 Green, 66 f.
 Grimaldi, 78
 Groups of comets, 179, 194
 Guillemin, 189

 Hale, Prof., 7, 29, 31 f., 68, 104
 Hall, A., 114, 140
 Hall, M., 159
 Halley, 74
 Halley's comet, 39, 179, 187 ff.,
 194 n.
 Hansen, 153
 Hansky, 52
 Harding, 40, 42, 160
 Helmholtz, 24
 Henry, 226
 Hercules, cluster in, 227 ff.
 Herschel, Sir John, 12, 227 f., 234
 Herschel, Sir William, 13, 114, 139,
 150 ff., 205 f., 208 f., 222, 237 ff.
 Hertzprung, 220
 Hipparchus, 224
 Hirn, 144
 Holmes's comet, 181
 Hour Glass, Sea of the (Mars), 109
 Huggins, Sir W., 238 f.
 Hull, 185
 Humboldt (lunar crater), 78
 Humboldt (traveller), 153, 234
 Huygens, 141, 148
 Hyades, 226, 247

 Icebergs and solar activity, 15
 Ice-caps of Mars, 14 f., 102, 108, 111
 Innes, 202
 Invar, 64
 Invention of telescope, 132
 Irregular movement of Mercury,
 44 ff.
 Island Universes, 228, 230, 235 f.,
 244 f.

 Japan, earthquake in, 22
 Jewel, L., 34

- Johannesburg comet. *See* Biela's comet
- John XXII, Pope, 189
- Joly, 35, 37, 89, 222
- Jovian family of comets, 176, 178 f.
- Jupiter, Chap. VII *passim*
 attracts comets, 176, 178
 life on, 130
 satellites, 132 ff., 147
 temperature, 130
- Kaiser, 102
- Kapteyn, 204, 207, 211, 245
- Keeler, 145, 240, 242
- Kelvin, Lord, 24, 205
- Kepler, 95, 116, 122, 162, 171
- Kepler's laws, 31, 34, 44, 48, 72, 116, 120, 135, 145, 153, 218
- Kirchhoff, 5, 26
- Kirkwood, 122, 146
- Koppen, 14
- Lagrange, 157
- Lalande, 151, 160
- Langley, 12, 82
- Laplace, 74 f., 151, 157, 187 f., 190
- Laplace's theory of cosmogony, 114, 134, 145 f., 240
- Lassell, 114, 134, 152, 159
- Latitude, terrestrial, not constant, 57
- Lebedew, 29
- Leibnitz Mountains (lunar), 80
- Lemonnier, 151
- Le Morvan, 86
- Length :
 astronomical unit of, 162
 of comets' tails, 184
- Lenicque, F., 197
- Leonids, 192
- Le Verrier, 45, 123, 153 ff., 166
- Lexell, 151
- Libration, 77
- Life :
 on Jupiter, 130
 on Mars, 113
- Light :
 equation of, 138
 pressure of, 29 f., 46, 69, 185 f., 241, 246
 velocity of, determined by means of Jupiter's satellites, 136 f.
 zodiacal, 30, 46
- Lindemann, MM., 245
- Linné, 93
- Lippershey, Hans, 132
- Livlander, 159
- Lockyer, Sir N., 16 f., 27, 102, 198, 213
- Loewy, 86, 168
- Longitude determined by means of Jupiter's satellites, 136
- Lorenz, 47
- Lowell, 103 ff., 110 f.
- Lunar. *See* Moon
- Lunatic, 99
- Lyra, annular nebula in, 210
- Lyraids, 193
- Macpherson, H., 245
- Magellanic Clouds, 232, 234 f.
- Magnetic action of Sun on planets, 67 ff.
 pole, Earth's, 68
- Magnitude of stars, 199
- Maraldi, 128
- Mare Crisium, 92
- Imbrium, 92
- Serenitatis, 92
- Marius, Simon, 132
- Mars, Chap. V *passim*
 canals, 102 ff., 111
 ice-caps, 14 f., 102, 108, 111
 life on, 113
 mountains, 101
- Martian group of Asteroids, 121
- Mass, 46
 of a planet determined by means of its satellites, 135 f.
 of comets, 181
 of Jupiter, 126
 of Mercury, 49
 of the Moon, 61, 79
 of Neptune, 159
 of the stars, 216 f.
 of the Sun, 2
 of Uranus, 151
 of Venus, 49
- Maurolycus, 78
- Maury, Miss, 219
- Maxwell, J. C., 29, 46 f., 69, 144
- Mayer, 23, 151 n.
- Méchain, 64
- Meldrum, 16
- Melotte, 133
- Mercury, 39 ff.
 irregular movement of, 44 ff.
 phases, 40
 spots, 40
 temperature, 43
- Messier, 227
- Messina, earthquake at, 22
- Meteorites, 195 ff.
- Metre, definition of, 65
- Meunier, S., 195, 197
- Milky Way, 200, 208 f., 221 f., 232, 240, 242, 244 ff.
 position of Sun in, 232
 size of, 228 ff.

- Millochau, 106
 Milne, Prof., 58
 Minor Planets. *See* Asteroids
 Mira Ceti, 220, 224
 Moestlin, 44
 Moissan, 197
 Moll, 42
 Moon, Chap. IV *passim*
 acceleration of orbit, 74
 changes on surface, 93 f.
 circuses, 78 ff., 91
 craters, 78 ff.
 distance, 72
 effect on the Earth, 58, 61 f., 95 ff.
 libration, 77
 mountain ranges, 80
 orbital plane, 73
 perturbations, 73
 revolution, 82
 ring mountains, 78 ff., 91
 rotation, 75
 seas, 78, 91
 size, 72, 78
 temperature, 81 f.
 volcanoes, 80, 93
 Morehouse's comet, 184, 186
 Motion :
 of the Sun, 1, 205 ff.
 of the stars, 203 ff.
 Mountain chain of Europe and Asia, 37
 ranges on the Moon, 80
 Moye, M., 223

 Nansen, F., 111
 Nasmyth, 79 f., 87
 Nebula in Orion, 237, 240, 245
 Nebulæ, 227, Chap. XVI *passim*
 constitution of, 238 f.
 distances of, 227 ff.
 planetary, 237, 240
 spiral, 239 ff.
 velocities of, 242, 244
 Nebulium, 239
 Neptune, 155 ff.
 discovery of, 153 ff.
 Newcomb, S., 159, 200, 205, 207 f., 228, 230
 Newton, 74
 Newton's law of attraction, 47 f.
 Nichols, 29, 185
 Nicholson, 135
 Nodes of lunar orbit, 74
 Novæ, 224 f., 242
 Nubecula Major, 234
 Minor, 234 f.
 Nucleus of a comet, 180 f.
 Nutation, 61 f.

 Obliquity of ecliptic, 62
 Olbers, Dr., 118, 121
 Opik, 159
 Opposition, 50
 Orion, nebula in, 237, 240, 245

 Palisa, 119
 Pallas, 118
 Palmer, 229
 Parallax, 164
 stellar, 201
 Paulsen, 69
 Pease, 220, 228
 Penumbra of sun-spot, 5
 Periodicity :
 of sun-spots, 10, 30, 35 f., 222
 of Sun's equatorial acceleration, 35
 Perrine, Dr., 133
 Perrotin, 103
 Perseids, 193
 Perturbations, lunar, 73
 of Uranus, 154 ff.
 Peters, 119
 Phases of Mercury, 40
 of Venus, 50
 Phobos, 114
 Photosphere, 4 ff.
 Piazzi, 117, 166
 Pickering, 51, 134, 149
 Planet :
 beyond Neptune, 160, 179
 mass of, determined by means of its satellites, 135 f.
 nearer than Mercury, 45
 Planetary nebulae, 237, 240
 Planets :
 Bode's law for distances of, 117
 magnetic action of the Sun on, 67
 Minor. *See* Asteroids
 Plateau's experiment, 146
 Platina, 190
 Pleiades, 226 f., 247
 Pliny, 190
 Poincaré, H., ix, 248
 Polar compression :
 of the Earth, 66
 of Jupiter, 126, 140
 of Neptune, 159
 of Saturn, 140
 of Uranus, 152
 Polar ice-caps of Mars, 14 f., 102, 108, 111
 Pole :
 Earth's magnetic, 68
 movement of the Earth's, 57 ff.
 star, 202
 Pollux, 216

Position of the Sun in the Milky Way, 232
 Pouillet, 12
 Precession, 61 f.
 Pressure of radiation. *See* Light, pressure of
 Prominences, solar, 7, 11, 29, 36
 Proper motions of the stars, 203 ff.
 Prosperin, 42
 Provence, earthquake in, 22
 Ptolemy (astronomer), 56
 Ptolemy (lunar crater), 78, 92
 Puiseux, 85 f., 91

 Radial displacement, 204
 Radiant point, 192
 Radio-activity, 27, 35, 38, 222
 Ramsay, Sir W., 26
 Retrogression, 55, 134, 176
 Reversing layer, 5 f.
 Riccioli, 44
 Richer, 165
 Rings of Saturn, 114, 123, 139, 141 ff.
 Ritchey, Dr., 94
 Roche, 144, 146
 Römer, 137 f., 156
 Rook Mountains (lunar), 81
 Rosse, Lord, 82, 114, 238 f.
 Rutherford, 26

 Sabine, 18
 San Francisco, earthquake at, 22
 Satellites :
 Jupiter's, used to determine longitude and velocity of light, 136 f.
 of Jupiter, 132 ff., 147
 of Mars, 114 f.
 of Neptune, 134, 159 ff.
 of Saturn, 148 f.
 of Uranus, 134
 used to determine mass of primary, 135 f.
 Saturn, Chap. VIII *passim*
 rings of, 114, 123, 139, 141 ff.
 Schär, 144
 Schiaparelli, 40, 51, 102 f., 192
 Schroeter, 40, 42
 Schuster, 69
 Seas :
 on Mars, 102, 106
 on Moon, 78, 91
 Secchi, 7, 102, 212 f., 224
 See, 159
 Seven planets, ancient belief in, 131
 Shape of the Earth, 63 ff.
 Shapley, H., 220 f., 227 ff., 242, 245
 Shooting stars, 191 ff., 196

Sirius, 126, 202, 212, 216, 218, 230
 Slipher, M., 152, 242
 Snow-caps on Mars, 14 f., 102, 108, 111
 Soddy, 27, 38
 Solar constant, 12 f.
 Spectro-heliograph, 7, 29
 Spiral nebula, 239 ff.
 Spoerer, 11
 Stars, Chap. XIII *passim*
 constitution of, 212
 distances of, 200 ff., 214, 220 f.
 proper motions of, 203 ff.
 volumes of, 216 f.
 See also Binary Stars, Clusters, Variable Stars
 Stefan's law, 4, 43, 130
 Stellar parallax, 201
 Stockwell, 75
 Stöfler, 78
 Stoney, J., 123
 Stratonoff, 211
 Stromgren, 173 f.
 Stroobant, 207, 211
 Struve, 148
 Suess, 66
 Sulton, 211
 Sun, Chap. I *passim*
 distance, 162 ff.
 equatorial acceleration, 3, 30, 33, 35, 127
 its activity periodic, 10, 30, 35 f., 222
 magnetic action on planets, 67 ff.
 mass, 2
 movement in space, 1, 205 ff.
 position in Milky Way, 232
 source of its heat, 23 ff.
 spots, 2, 5 f., 10 f., 21, 30 f., 33, 35 f., 222
 See also Chromosphere, Corona, Photosphere, Prominences, Solar Constant
 Syrtis Major, 109

 Tails of comets, 184 ff.
 Tangential displacement, 204
 Tears of Saint Lawrence, 193
 Telescope, invention of, 132
 Tempel's comet I, 193
 its eccentricity, 120
 Terby, 102
 Termier, P., 197
 Tetrahedral theory of Earth, 66
 Theaetetus, 93
 Theophilus, 92
 Thirion, 188
 Thollon, 103
 Thomson, Sir J. J., 47

- Three bodies, problem of, 73
 Tides, 95 f.
 their effect on Earth's rotation, 56
 Tisserand, xiv, 159
 Titius, 117
 Toucanus, cluster in, 229
 Transits :
 of Mercury, 42, 44
 of Venus, 50, 165
 Trojan group of asteroids, 121, 167
 Tuttle's comet, 178, 193
 Tycho, 85, 92

 Universes, other, 200, 228, 230, 235 f., 244 f.
 Uranus, 150 ff.
 discovery of, 117, 150 f.
 Urban II, Pope, 189

 Van Maanen, 245
 Variable stars, 11, 36, 219 ff., 229, 235
 Vega, 202, 207, 212, 216
 Velocities :
 of nebulae, 242, 244
 of star clusters, 242

 Velocity of light determined by means of Jupiter's satellites, 136 f.
 Venus, 49 ff.
 atmosphere of, 50
 climate, 51
 eccentricity of its orbit, 39
 phases, 50
 transits, 50, 165
 Véry, 82, 245
 Volcanic eruptions, 20 f., 37, 67
 Volcanoes, lunar, 80, 93
 Volume of Sun, 2
 of stars, 216 f.
 Vortex movement in chromosphere, 31 f.

 Watson, Prof., 119
 Williams, S., 140
 Wine yield in France, 14, 21
 Witt, Dr., 166
 Wolf (XVIII cent.), 117
 Wolf (XIX cent.), 119
 Wolf's law. *See* Bode's law

 Young, 34

 Zinner's comet, 178
 Zodiacal light, 30, 46

METHUEN'S GENERAL LITERATURE

A SELECTION OF MESSRS. METHUEN'S PUBLICATIONS

This Catalogue contains only a selection of the more important books published by Messrs. Methuen. A complete catalogue of their publications may be obtained on application.

PART I. GENERAL LITERATURE

Allen (R. Wilberforce)

METHODISM AND MODERN WORLD PROBLEMS. *Crown 8vo. 7s. 6d. net.*

Anstey (F.)

THE LAST LOAD. *Fcap 8vo. 5s. net.*

Armstrong (W. W.)

THE ART OF CRICKET. *Crown 8vo. 3s. net.*

Bain (F. W.)

A DIGIT OF THE MOON. THE DESCENT OF THE SUN. A HEIFER OF THE DAWN. IN THE GREAT GOD'S HAIR. A DRAUGHT OF THE BLUE. AN ESSENCE OF THE DUSK. AN INCARNATION OF THE SNOW. A MINE OF FAULTS. THE ASHES OF A GOD. BUBBLES OF THE FOAM. A SYRUP OF THE BEES. THE LIVERY OF EVE. THE SUBSTANCE OF A DREAM. *All Fcap. 8vo. 5s. net.* AN ECHO OF THE SPHERES. *Wide Demy 8vo. 10s. 6d. net.*

Baker (C. H. Collins)

CROME. Illustrated. *Quarto. £5 5s. net.*

Balfour (Sir Graham)

THE LIFE OF ROBERT LOUIS STEVENSON. *Twentieth Edition. In one Volume. Cr. 8vo. Buckram, 7s. 6d. net.*

Belloc (Hilaire)

PARIS. THE PYRENEES. *Each 8s. 6d. net.* ON NOTHING. HILLS AND THE SEA. ON SOMETHING. FIRST AND LAST. THIS AND THAT AND THE OTHER. ON. *Each 3s. 6d. net.* ON EVERYTHING. ON ANYTHING. *Each 6s. net.* MARIE ANTOINETTE. *18s. net.* A HISTORY OF ENGLAND. *In 4 vols. Vols. I and II. 15s. net each.*

Birmingham (George A.)

A WAYFARER IN HUNGARY. Illustrated. *Crown 8vo. 8s. 6d. net.* SPILLIKINS. *Fcap. 8vo. 5s. net.*

Bowen (Frank C.)

THE KING'S NAVY. Illustrated. *Fcap. 4to. 7s. 6d. net.*

Brinton (Selwyn)

THE GOLDEN AGE OF THE MEDICI. Illustrated. *Demy 8vo. 15s. net.*

Bulley (M. H.)

ART AND COUNTERFEIT. Illustrated.
Demy 4to. 15s. net.

Campbell (Olwen Ward)

SHELLEY AND THE UNROMANTICS.
Illustrated. *Second Edition, Revised.*
Demy 8vo. 16s. net.

Chandler (Arthur), D.D., late Lord Bishop of Bloemfontein

ARA CÆLLI 5s. net. FAITH AND EXPERIENCE. 5s. net. THE CULT OF THE PASSING MOMENT. 6s. net. THE ENGLISH CHURCH AND REUNION. 5s. net. SCALA MUNDI. 4s. 6d. net.

Chesterton (G. K.)

THE BALLAD OF THE WHITE HORSE. ALL THINGS CONSIDERED. TREMENDOUS TRIFLES. FANCIES VERSUS FADS. CHARLES DICKENS. *All Fcap. 8vo. 3s. 6d. net.* ALARMS AND DISCURSIONS. A MISCELLANY OF MEN. THE USES OF DIVERSITY. THE OUTLINE OF SANITY. *All Fcap. 8vo. 6s. net.* A GLEAMING COHORT. *Fcap 8vo. 2s. 6d. net.* WINE, WATER, AND SONG. *Fcap. 8vo. 1s. 6d. net.*

Clutton-Brock (A.)

WHAT IS THE KINGDOM OF HEAVEN? ESSAYS ON ART. SHAKESPEARE'S HAMLET. *Each 5s. net.* ESSAYS ON BOOKS. MORE ESSAYS ON BOOKS. ESSAYS ON LIFE. ESSAYS ON RELIGION. *Each 6s. net.* SHELLEY, THE MAN AND THE POET. 7s. 6d. net.

Cowling (George H.)

A PREFACE TO SHAKESPEARE. Illustrated.
Crown 8vo. 5s. net.

Dark (Sidney) and Grey (Rowland)

W. S. GILBERT: HIS LIFE AND LETTERS. *Second Edition.* Demy 8vo. 15s. net.

Dolls' House (The Queen's)

THE BOOK OF THE QUEEN'S DOLLS' HOUSE. Vol. I. THE HOUSE, Edited by A. C. BENSON, C.V.O., and Sir LAWRENCE WEAVER, K.B.E. Vol. II. THE LIBRARY, Edited by E. V. LUCAS. Profusely Illustrated. A Limited Edition. *Crown 4to. £6 6s. net.*

EVERYBODY'S BOOK OF THE QUEEN'S DOLLS' HOUSE. An abridged edition of the above. Illustrated. *Crown 4to. 5s. net.*

Edwardes (Tickner)

THE LORE OF THE HONEYBEE. *Thirteenth Edition.* *Crown 8vo. 7s. 6d. net.* BEEKEEPING FOR ALL. *Crown 8vo. 3s. 6d. net.* THE BEE-MASTER OF

WARRILOW. *Third Edition.* *Crown 8vo. 7s. 6d. net.* All Illustrated. BEEKEEPING DO'S AND DON'TS. *Fcap. 8vo. 2s. 6d. net.*

Einstein (Albert)

RELATIVITY: THE SPECIAL AND GENERAL THEORY. *Crown 8vo. 5s. net.* SIDELIGHTS ON RELATIVITY. *Crown 8vo. 3s. 6d. net.* THE MEANING OF RELATIVITY. *Crown 8vo. 5s. net.*

Other books on the Einstein Theory AN INTRODUCTION TO THE THEORY OF RELATIVITY. By LYNDON BOLTON. *Crown 8vo. 5s. net.*

THE PRINCIPLE OF RELATIVITY. By A. EINSTEIN, H. A. LORENTZ, H. MINKOWSKI and H. WEYL. With Notes by A. SOMMERFELD. *Demy 8vo. 12s. 6d. net.*

Write for Complete List

Fitzgerald (Edward)

THE RUBA'YAT OF OMAR KHAYYAM. Illustrated by EDMUND J. SULLIVAN. *Wide Crown 8vo. 10s. 6d. net.*

Forrest (H. Edward)

THE OLD HOUSES OF STRATFORD-UPON-AVON. Illustrated. *Crown 8vo. 7s. 6d. net.* Also an edition limited to 250 copies, *Fcap. 4to. 21s. net.*

Fyleman (Rose)

FAIRIES AND CHIMNEYS. THE FAIRY GREEN. THE FAIRY FLUTE. THE RAINBOW CAT. EIGHT LITTLE PLAYS FOR CHILDREN. FORTY GOOD-NIGHT TALES. FAIRIES AND FRIENDS. THE ADVENTURE CLUB. *Each 3s. 6d. net.* A SMALL CRUSE, 4s. 6d. net. THE ROSE FYLEMAN FAIRY BOOK. Illustrated. *Crown 4to. 10s. 6d. net.*

Gibbon (Edward)

THE DECLINE AND FALL OF THE ROMAN EMPIRE. With Notes, Appendixes, and Maps, by J. B. BURY. Illustrated. Seven volumes. *Demy 8vo. 15s. net* each volume. Also, unillustrated. *Crown 8vo. 7s. 6d. net* each volume.

Glover (T. R.)

THE CONFLICT OF RELIGIONS IN THE EARLY ROMAN EMPIRE. POETS AND PURITANS. FROM PERICLES TO PHILIP. VIRGIL. *Each 10s. 6d. net.*

Gotch (J. A.)

OLD ENGLISH HOUSES. Illustrated. *Demy 8vo. 16s. net.* Also an edition limited to 50 copies, £2 2s. net.

Graham (Harry)

THE WORLD WE LAUGH IN: More Departmental Ditties. Illustrated by "FISH." *Sixth Edition. Fcap. 8vo. 5s. net.*

Grahame (Kenneth)

THE WIND IN THE WILLOWS. *Nineteenth Edition. Crown 8vo. 7s. 6d. net.* Also, Illustrated by NANCY BARNHART. *Small 4to. 10s. 6d. net.*

Hadfield (J. A.)

PSYCHOLOGY AND MORALS. *Sixth Edition. Crown 8vo. 6s. net.*

Hall (H. R.)

THE ANCIENT HISTORY OF THE NEAR EAST. *Sixth Edition, Revised. Demy 8vo. £1 1s. net.* THE CIVILIZATION OF GREECE IN THE BRONZE AGE. Illustrated. *Demy 8vo. 10s. 6d. net.*

Hamer (Sir W. H.), and Hutt (C. W.)

A MANUAL OF HYGIENE. Illustrated. *Demy 8vo. £1 10s. net.*

Hays (Mary)

THE LOVE LETTERS OF MARY HAYS. Edited by A. F. WEDD. *Demy 8vo. 12s. 6d. net.*

Hewlett (Maurice)

THE LETTERS OF MAURICE HEWLETT. Edited by LAURENCE BINYON. Illustrated. *Demy 8vo. 18s. net.*

Hind (A. M.)

A CATALOGUE OF REMBRANDT'S ETCHINGS. Two Vols. Profusely Illustrated. *Wide Royal 8vo. £1 15s. net.*

Holdsworth (W. S.)

A HISTORY OF ENGLISH LAW. Nine Volumes. *Demy 8vo. £1 5s. net each.*

Hudson (W. H.)

A SHEPHERD'S LIFE. Illustrated. *Demy 8vo. 10s. 6d. net.* Also, unillustrated, *Fcap. 8vo. 3s. 6d. net.*

Hutton (Edward)

THE CITIES OF SICILY. Illustrated. *10s. 6d. net.* MILAN AND LOMBARDY. THE CITIES OF ROMAGNA AND THE MARCHES. SIENA AND SOUTHERN TUSCANY. VENICE AND VENETIA. THE CITIES OF SPAIN. NAPLES AND SOUTHERN ITALY. Illustrated. *Each, 8s. 6d. net.* A WAYFARER IN UNKNOWN TUSCANY. THE CITIES OF UMBRIA. COUNTRY WALKS ABOUT FLORENCE. ROME. FLORENCE AND NORTHERN TUSCANY. Illustrated. *Each, 7s. 6d. net.*

Imms (A. D.)

A GENERAL TEXTBOOK OF ENTOMOLOGY. Illustrated. *Royal 8vo. £1 16s. net.*

Inge (W. R.), D.D., Dean of St. Paul's
CHRISTIAN MYSTICISM. (The Bampton Lectures of 1899.) *Sixth Edition. Crown 8vo. 7s. 6d. net.*

Kipling (Rudyard)

BARRACK-ROOM BALLADS. *241st Thousand.*

THE SEVEN SEAS. *172nd Thousand.*

THE FIVE NATIONS. *138th Thousand.*

DEPARTMENTAL DITTIES. *111th Thousand.*

THE YEARS BETWEEN. *95th Thousand.* Four Editions of these famous volumes of poems are now published, viz.:—*Crown 8vo. Buckram, 7s. 6d. net. Fcap. 8vo. Cloth, 6s. net. Leather, 7s. 6d. net.* Service Edition. Two volumes each book. *Square Fcap. 8vo. 3s. net each volume.*

A KIPLING ANTHOLOGY—Verse. *Fcap. 8vo. Cloth, 6s. net. Leather, 7s. 6d. net.*

TWENTY POEMS FROM RUDYARD KIPLING. *423rd Thousand. Fcap. 8vo. 1s. net.*

A CHOICE OF SONGS. *Second Edition. Fcap. 8vo. 2s. net.*

Lamb (Charles and Mary)

THE COMPLETE WORKS. Edited by E. V. LUCAS. A New and Revised Edition in Six Volumes. With Frontispieces. *Fcap. 8vo. 6s. net each.*

The volumes are: I. MISCELLANEOUS PROSE. II. ELIA AND THE LAST ESSAYS OF ELIA. III. BOOKS FOR CHILDREN. IV. PLAYS AND POEMS. V. and VI. LETTERS.

SELECTED LETTERS. Chosen and Edited by G. T. CLAPTON. *Fcap. 8vo. 3s. 6d. net.*

THE CHARLES LAMB DAY BOOK
Compiled by E. V. LUCAS. *Fcap. 8vo. 6s. net.*

Lankester (Sir Ray)

SCIENCE FROM AN EASY CHAIR. SCIENCE FROM AN EASY CHAIR: Second Series. DIVERSIONS OF A NATURALIST. GREAT AND SMALL THINGS. Illustrated. *Crown 8vo. 7s. 6d. net.* SECRETS OF EARTH AND SEA. Illustrated. *Crown 8vo. 8s. 6d. net.*

Lodge (Sir Oliver)

MAN AND THE UNIVERSE (*Twentieth Edition*); THE SURVIVAL OF MAN (*Seventh Edition*). Each Crown 8vo. 7s. 6d. net. RAYMOND (*Thirteenth Edition*). Demy 8vo. 10s. 6d. net. RAYMOND REVISED. Crown 8vo. 6s. net. RELATIVITY (*Third Edition*). Fcap. 8vo. 1s. net.

Lucas (E. V.)

THE LIFE OF CHARLES LAMB. 2 Vols. £1 1s. net. EDWIN AUSTIN ABBEY, R.A. 2 Vols. £6 6s. net. VERMEER OF DELFT. 10s. 6d. net. A WANDERER IN ROME. A WANDERER IN HOLLAND. A WANDERER IN LONDON. LONDON REVISITED (Revised). A WANDERER IN PARIS. A WANDERER IN FLORENCE. A WANDERER IN VENICE. Each 10s. 6d. net. A WANDERER AMONG PICTURES. 8s. 6d. net. E. V. LUCAS'S LONDON. £1 net. INTRODUCING LONDON. 2s. 6d. net. THE OPEN ROAD. 6s. net. Also, illustrated. 10s. 6d. net. Also, India Paper. Leather, 7s. 6d. net. THE FRIENDLY TOWN. FIRESIDE AND SUNSHINE. CHARACTER AND COMEDY. Each 6s. net. THE GENTLEST ART. 6s. 6d. net. And THE SECOND POST. 6s. net. Also, together in one volume 7s. 6d. net. HER INFINITE VARIETY. GOOD COMPANY. ONE DAY AND ANOTHER. OLD LAMPS FOR NEW. LOITERER'S HARVEST. CLOUD AND SILVER. A BOSWELL OF BAGHDAD. "TWIXT EAGLE AND DOVE. THE PHANTOM JOURNAL. GIVING AND RECEIVING. LUCK OF THE YEAR. ENCOUNTERS AND DIVERSIONS. ZIGZAGS IN FRANCE. 365 (AND ONE MORE). Each 6s. net. SPECIALLY SELECTED. URBANITIES. Each, illustrated by G. L. STAMPA, 7s. 6d. net. YOU KNOW WHAT PEOPLE ARE. Illustrated by GEORGE MORROW. 5s. net. THE SAME STAR: A Comedy in Three Acts. 3s. 6d. net. THE BRITISH SCHOOL. 6s. net. LITTLE BOOKS ON GREAT MASTERS. Each 5s. net. ROVING EAST AND ROVING WEST. 5s. net. PLAYTIME AND COMPANY. 7s. 6d. net. See also Dolls' House (The Queen's) and Lamb (Charles)

Lynd (Robert)

THE MONEY BOX. THE ORANGE TREE. Each Fcap. 8vo. 6s. net. THE BLUE LION. THE PEAL OF BELLS. Each Fcap. 8vo. 3s. 6d. net.

Marie Louise (H.H. Princess)

A CHOICE OF CAROLS. Fcap. 4to. 2s. 6d. net. LETTERS FROM THE GOLD COAST. Illustrated. Demy 8vo. 16s. net.

McDougall (William)

AN INTRODUCTION TO SOCIAL PSYCHOLOGY (*Twentieth Edition, Revised*), 10s. 6d. net. NATIONAL WELFARE AND NATIONAL DECAY. 6s. net. AN OUTLINE OF PSYCHOLOGY. 12s. net. AN OUTLINE OF ABNORMAL PSYCHOLOGY. 15s. net. BODY AND MIND (*Fifth Edition*). 12s. 6d. net. ETHICS AND SOME MODERN WORLD PROBLEMS. 7s. 6d. net.

Mackenzie-Rogan (Lt.-Col. J.)

FIFTY YEARS OF ARMY MUSIC. Illustrated. Demy 8vo. 15s. net.

Maeterlinck (Maurice)

THE BLUE BIRD. 6s. net. Also, illustrated by F. CAYLEY ROBINSON. 10s. 6d. net. MARY MAGDALENE. 5s. net. DEATH. 3s. 6d. net. OUR ETERNITY. 6s. net. THE UNKNOWN GUEST. 6s. net. POEMS. 5s. net. THE WRACK OF THE STORM. 6s. net. THE MIRACLE OF ST. ANTHONY. 3s. 6d. net. THE BURGOMASTER OF STILEMONDE. 5s. net. THE BETROTHAL. 6s. net. MOUNTAIN PATHS. 6s. net. THE STORY OF TYLTYL. £1 1s. net. THE GREAT SECRET. 7s. 6d. net. THE CLOUD THAT LIFTED AND THE POWER OF THE DEAD. 7s. 6d. net.

Masefield (John)

ON THE SPANISH MAIN. 8s. 6d. net. A SAILOR'S GARLAND. 6s. net. SEA LIFE IN NELSON'S TIME. 5s. net.

Methuen (Sir A.)

AN ANTHOLOGY OF MODERN VERSE. 107th Thousand. SHAKESPEARE TO HARDY: An Anthology of English Lyrics. 15th Thousand. Each Fcap. 8vo. Cloth, 6s. net. Leather, 7s. 6d. net.

Milne (A. A.)

NOT THAT IT MATTERS. IF I MAY. Each 3s. 6d. net. WHEN WE WERE VERY YOUNG. Illustrated by E. H. SHEPARD. Thirteenth Edition. 117th Thousand. 7s. 6d. net. Leather, 10s. 6d. net. FOR THE LUNCHEON INTERVAL: CRICKET AND OTHER VERSES. 1s. 6d. net.

Milne (A. A.) and Fraser-Simson (H.)
FOURTEEN SONGS FROM "WHEN WE WERE VERY YOUNG." (*Eighth Edition*). MORE SONGS FROM "WHEN WE WERE VERY YOUNG." Words by A. A. Milne. Music by H. Fraser-Simson. Each *Royal 4to.* 7s. 6d. *net.* THE KING'S BREAKFAST. *Crown 4to.* 3s. 6d. *net.*

Montague (C. E.)
DRAMATIC VALUES. *Crown 8vo.* 7s. 6d. *net.*

Newman (Tom)
HOW TO PLAY BILLIARDS. Illustrated. *Crown 8vo.* 8s. 6d. *net.* BILLIARD DO'S AND DON'TS. 2s. 6d. *net.*

Oman (Sir Charles)
A HISTORY OF THE ART OF WAR IN THE MIDDLE AGES, A.D. 378-1485. *Second Edition*, Revised and Enlarged. 2 Vols. Illustrated. *Demy 8vo.* £1 16s. *net.*

Oxenham (John)
BEES IN AMBER. *Small Pott 8vo.* 2s. *net.* ALL'S WELL. THE KING'S HIGHWAY. THE VISION SPLENDID. THE FIERY CROSS. HIGH ALTARS. HEARTS COURAGEOUS. ALL CLEAR! *Each Small Pott 8vo.* *Paper*, 1s. 3d. *net.* Cloth, 2s. *net.* WINDS OF THE DAWN. 2s. *net.*

Perry (W. J.)
THE ORIGIN OF MAGIC AND RELIGION. THE GROWTH OF CIVILIZATION (*Second Edition*). *Each 6s. net.* THE CHILDREN OF THE SUN. 18s. *net.*

Petrie (Sir Flinders)
A HISTORY OF EGYPT. In 6 Volumes. Vol. I. FROM THE 1ST TO THE XVIth DYNASTY. *Eleventh Edition*, Revised. 12s. *net.* Vol. II. THE XVIIth AND XVIIIth DYNASTIES. *Seventh Edition*, Revised. 9s. *net.* Vol. III. XIXth TO XXXth DYNASTIES. *Third Edition.* 12s. *net.* Vol. IV. PTOLEMAIC EGYPT. By EDWYN BEVAN. 10s. 6d. *net.* Vol. V. EGYPT UNDER ROMAN RULE. J. G. MILNE. *Third Edition*, Revised. 12s. *net.* Vol. VI. EGYPT IN THE MIDDLE AGES. STANLEY LANE POOLE. *Fourth Edition.* 10s. *net.*

Raleigh (Sir Walter)
THE LETTERS OF SIR WALTER RALEIGH. Edited by LADY RALEIGH. Two Vols. Illustrated. (*Second Edition*.) *Demy 8vo.* £1 10s. *net.*

Rice-Oxley (L.)
OXFORD RENOWNED. Illustrated. *Demy 8vo.* 18s. *net.*

Smith (Adam)
THE WEALTH OF NATIONS. Edited by EDWIN CANNAN. 2 Vols. *Demy 8vo.* £1 5s. *net.*

Smith (C. Fox)
SAILOR TOWN DAYS. SEA SONGS AND BALLADS. A BOOK OF FAMOUS SHIPS. SHIP ALLEY. *Each*, illustrated, 6s. *net.* FULL SAIL. Illustrated. 5s. *net.* TALES OF THE CLIPPER SHIPS. 5s. *net.* THE RETURN OF THE "CUTTY SARK." Illustrated. 3s. 6d. *net.*

Sommerfeld (Arnold)
ATOMIC STRUCTURE AND SPECTRAL LINES. *Demy 8vo.* £1 12s. *net.*

Stevens (F. E.)
THE NEW FOREST BEAUTIFUL. Illustrated. *Crown 8vo.* 8s. 6d. *net.*

Stevenson (R. L.)
THE LETTERS. Edited by Sir SIDNEY COLVIN. 4 Vols. *Fcap. 8vo.* *Each* 6s. *net.*

Stratton (F. J. M.)
ASTRONOMICAL PHYSICS. *Demy 8vo.* 12s. 6d. *net.*

Surtees (R. S.)
HANDLEY CROSS. MR. SPONGE'S SPORTING TOUR. ASK MAMMA. MR. FACEY ROMFORD'S HOUNDS. PLAIN OR RINGLET'S? HILLINGDON HALL. *Each*, illustrated, 7s. 6d. *net.* JORROCK'S JAUNTS AND JOLLITIES. HAWBUCK GRANGE. *Each*, illustrated, 6s. *net.*

Thomson (J. Arthur)
WHAT IS MAN? 6s. 6d. *net.* SCIENCE AND RELIGION. 7s. 6d. *net.*

Tilden (W. T.)
THE ART OF LAWN TENNIS. SINGLES AND DOUBLES. *Each*, illustrated, 6s. *net.* THE COMMON SENSE OF LAWN TENNIS. Illustrated. 5s. *net.*

Tileston (Mary W.)
DAILY STRENGTH FOR DAILY NEEDS. 31st *Edition.* 3s. 6d. *net.* *India Paper*, *Leather*, 6s. *net.*

Underhill (Evelyn)
MYSTICISM (*Tenth Edition*). 15s. *net.* THE LIFE OF THE SPIRIT AND THE LIFE OF TO-DAY (*Sixth Edition*). 7s. 6d. *net.*

Vardon (Harry)
HOW TO PLAY GOLF. Illustrated. 18th *Edition.* *Crown 8vo.* 5s. *net.*

Waterhouse (Elizabeth)

A LITTLE BOOK OF LIFE AND DEATH.
22nd Edition. Small Pott 8vo. 2s. 6d.
net.

Wilde (Oscar).

THE WORKS. In 16 Vols. Each 6s. 6d.
net.

I. LORD ARTHUR SAVILE'S CRIME AND
THE PORTRAIT OF MR. W. H. II. THE
DUCHESS OF PADUA. III. POEMS. IV.
LADY WINDERMERE'S FAN. V. A
WOMAN OF NO IMPORTANCE. VI. AN
IDEAL HUSBAND. VII. THE IMPOR-
TANCE OF BEING EARNEST. VIII. A

HOUSE OF POMEGRANATES. IX. IN-
TENTIONS. X. DE PROFUNDIS AND
PRISON LETTERS. XI. ESSAYS. XII.
SALOME, A FLORENTINE TRAGEDY, and
LA SAINTE COURTISANE. XIII. A
CRITIC IN PALL MALL. XIV. SELECTED
PROSE OF OSCAR WILDE. XV. ART AND
DECORATION. XVI. FOR LOVE OF THE
KING. (5s. net.)

Williamson (G. C.)

THE BOOK OF FAMILLE ROSE. Richly
Illustrated. Demy 4to. £8 8s. net.
Also a limited edition, £12 12s. net.

PART II. A SELECTION OF SERIES

The Antiquary's Books

Each, illustrated, Demy 8vo. 10s. 6d. net.
A series of volumes dealing with various
branches of English Antiquities, com-
prehensive and popular, as well as
accurate and scholarly.

The Arden Shakespeare

Edited by W. J. CRAIG and R. H. CASE.
Each, wide Demy 8vo. 6s. net.

The Ideal Library Edition, in single
plays, each edited with a full Introduc-
tion, Textual Notes and a Commentary
at the foot of the page. Now complete
in 39 Vols.

Classics of Art

Edited by J. H. W. LAING. Each, pro-
fusely illustrated, wide Royal 8vo. 15s.
net to £3 3s. net.

A Library of Art dealing with Great
Artists and with branches of Art.

The "Complete" Series

Demy 8vo. Fully illustrated.

AIRMAN. 16s. net. AMATEUR BOXER.
10s. 6d. net. BILLIARD PLAYER. 10s. 6d.
net. COOK. 10s. 6d. net. FOXHUNTER.
16s. net. GOLFER. 12s. 6d. net. HOCKEY
PLAYER. 10s. 6d. net. HORSEMAN. 15s.
net. JUJITSUAN (Cr. 8vo). 5s. net.
LAWN TENNIS PLAYER. 12s. 6d. net.
MOTORIST. 10s. 6d. net. MOUNTAIN-
EER. 18s net. OARSMAN. 12s. 6d. net.
PHOTOGRAPHER. 12s. 6d. net. RUGBY
FOOTBALLER, ON THE NEW ZEALAND
SYSTEM. 12s. 6d. net. SHOT. 16s. net.
SWIMMER. 10s. 6d. net. YACHTSMAN.
15s. net.

The Connoisseur's Library

With numerous Illustrations. Wide
Royal 8vo. £1 11s. 6d. net each vol.
EUROPEAN ENAMELS. FINE BOOKS.
GLASS. GOLDSMITHS' AND SILVER-
SMITHS' WORK. IVORIES. JEWELLERY.
MEZZOTINTS. PORCELAIN. SEALS.

The Do's and Dont's Series

Fcap. 8vo. 2s. 6d. net each.

This series, although only in its in-
fancy, is already famous. In due course
it will comprise clear, crisp, informative
volumes on all the activities of life.

Write for full list

The Library of Devotion

Handy editions of the great Devotional
books, well edited. Small Pott 8vo.
3s. net and 3s. 6d. net.

Little Books on Art

Well Illustrated. Demy 16mo. Each
5s. net.

Modern Masterpieces

Fcap. 8vo. 3s. 6d. each volume.

Pocketable Editions of Works by A. A.
MILNE, JOSEPH CONRAD, ARNOLD
BENNETT, G. K. CHESTERTON, E. V.
LUCAS, HILAIRE BELLOC, W. H. HUDSON,
ROBERT LYND, R. L. STEVENSON, JACK
LONDON and E. V. KNOX.

Sport Series

Mostly Illustrated. Fcap. 8vo. 2s. net
to 5s. net each.

Handy books on all branches of sport by
experts.

Methuen's Half-Crown Library
Crown 8vo and Fcap. 8vo.

Methuen's Two Shilling Library
Fcap. 8vo.

Two series of cheap editions of popular books.

Write for complete lists

The Wayfarer Series of Books for Travellers

Crown 8vo. 7s. 6d. net each. Well illustrated and with maps. The volumes are :—Alsace, Czecho-Slovakia,

The Dolomites, Egypt, Hungary, The Loire, Provence, Spain, Sweden, Switzerland, Unfamiliar Japan, Unknown Tuscany.

The Westminster Commentaries

Demy 8vo. 8s. 6d. net to 16s. net.

Edited by W. LOCK, D.D. and D. C. SIMPSON, D.D.

The object of these commentaries is primarily to interpret the author's meaning to the present generation, taking the English text in the Revised Version as their basis.

THE LITTLE GUIDES

Small Pott 8vo. Illustrated and with Maps

4s. net mostly

THE 62 VOLUMES IN THE SERIES ARE :—

BEDFORDSHIRE AND HUNTINGDONSHIRE
BERKSHIRE
BRITTANY
BUCKINGHAMSHIRE
CAMBRIDGE AND COLLEGES
CAMBRIDGESHIRE
CATHEDRAL CITIES OF ENGLAND AND WALES 6s. net
CHANNEL ISLANDS 5s. net
CHESHIRE 5s. net
CORNWALL
CUMBERLAND AND WESTMORLAND 6s. net
DERBYSHIRE
DEVON
DORSET 5s. 6d. net
DURHAM 6s. net.
ENGLISH LAKES 6s. net
ESSEX 5s. net
GLOUCESTERSHIRE
GRAY'S INN AND LINCOLN'S INN 6s. net
HAMPSHIRE
HEREFORDSHIRE 4s. 6d. net
HERTFORDSHIRE
ISLE OF MAN 6s. net.
ISLE OF WIGHT
KENT 5s. net
KERRY
LANCASHIRE 6s. net
LEICESTERSHIRE AND RUTLAND 5s. net
LINCOLNSHIRE 6s. net
LONDON 5s. net.
MALVERN COUNTRY

MIDDLESEX
MONMOUTHSHIRE 6s. net
NORFOLK 5s. net
NORMANDY 5s. net
NORTHAMPTONSHIRE
NORTHUMBERLAND 7s. 6d. net
NORTH WALES 6s. net
NOTTINGHAMSHIRE
OXFORD AND COLLEGES
OXFORDSHIRE
ROME 5s. net
ST. PAUL'S CATHEDRAL
SHAKESPEARE'S COUNTRY
SHROPSHIRE
SICILY
SNOWDONIA 6s. net
SOMERSET
SOUTH WALES
STAFFORDSHIRE 5s. net
SUFFOLK
SURREY 5s. net.
SUSSEX
TEMPLE
WARWICKSHIRE 5s. net
WESTMINSTER ABBEY
WILTSHIRE 6s. net
WORCESTERSHIRE 6s. net
YORKSHIRE EAST RIDING 5s. net
YORKSHIRE NORTH RIDING
YORKSHIRE WEST RIDING 7s. 6d. net
YORK 6s. net

METHUEN & CO. LTD., 36 ESSEX STREET, LONDON, W.C.2.

Astron.

M.

207292

Author Moreux, Theodore

Title Astronomy to-day.

University of Toronto
Library

DO NOT
REMOVE
THE
CARD
FROM
THIS
POCKET

Acme Library Card Pocket
Under Pat "Ref. Index File"
Made by LIBRARY BUREAU

*... We have
Harris J. H. 1.*

